

New Physics after the LHC Now and Future



Shufang Su • U. of Arizona

Next Step in the Energy Frontier - Hadron Collider
August 28, Fermilab

Outline

Where is the physics beyond the SM?

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• What did we learn from LHC 7/8 TeV (20 fb^{-1}) ?

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High luminosity LHC, Higgs factory, Precision machine, Higher energies

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© Higgs-related



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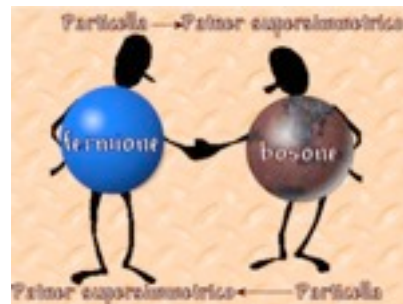
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◎ Higgs-related



◎ top partners (naturalness)



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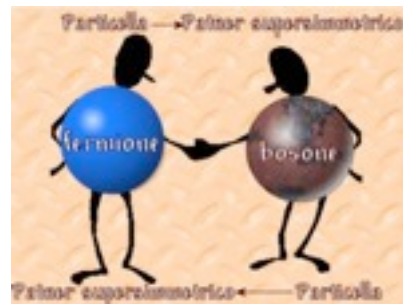
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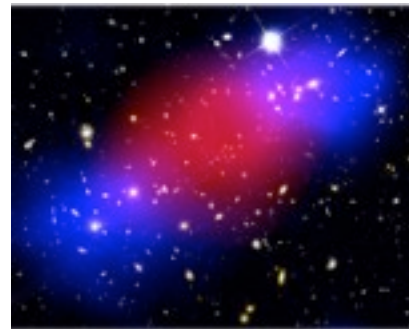
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◎ top partners (naturalness)



◎ dark matter



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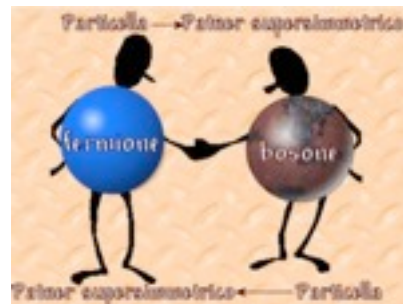
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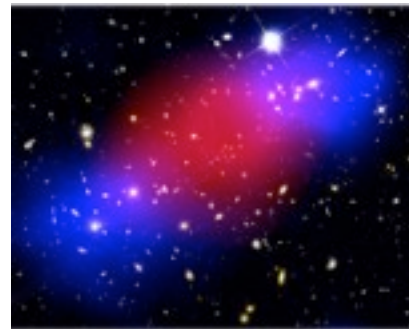
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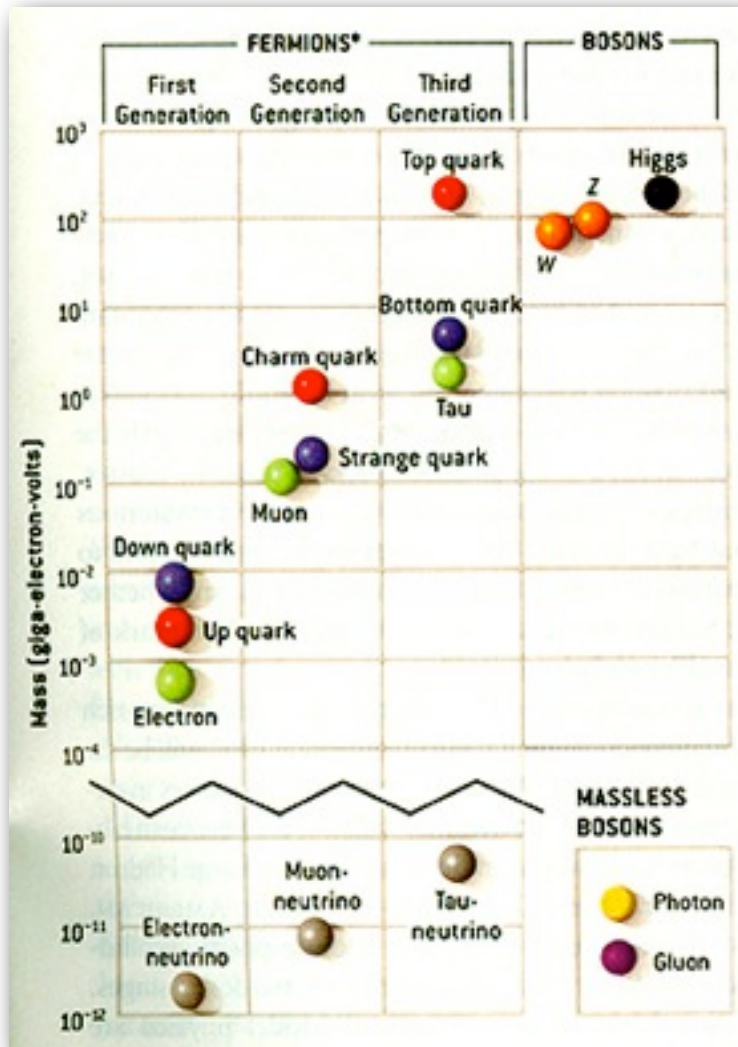


◎ other BSM



Standard Model

Image credit: Gordon Kane, Scientific American, June 2003.



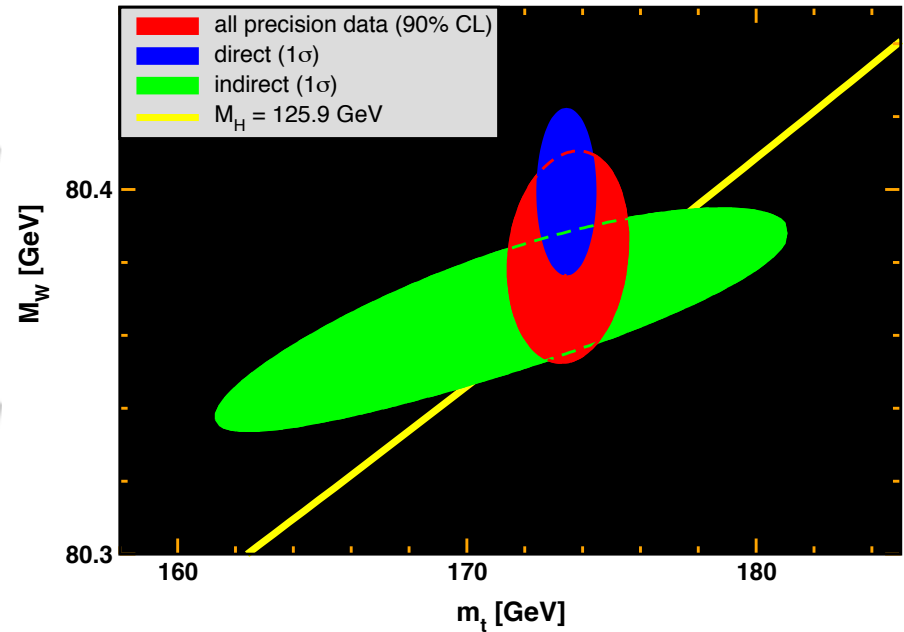
TeV

GeV

MeV

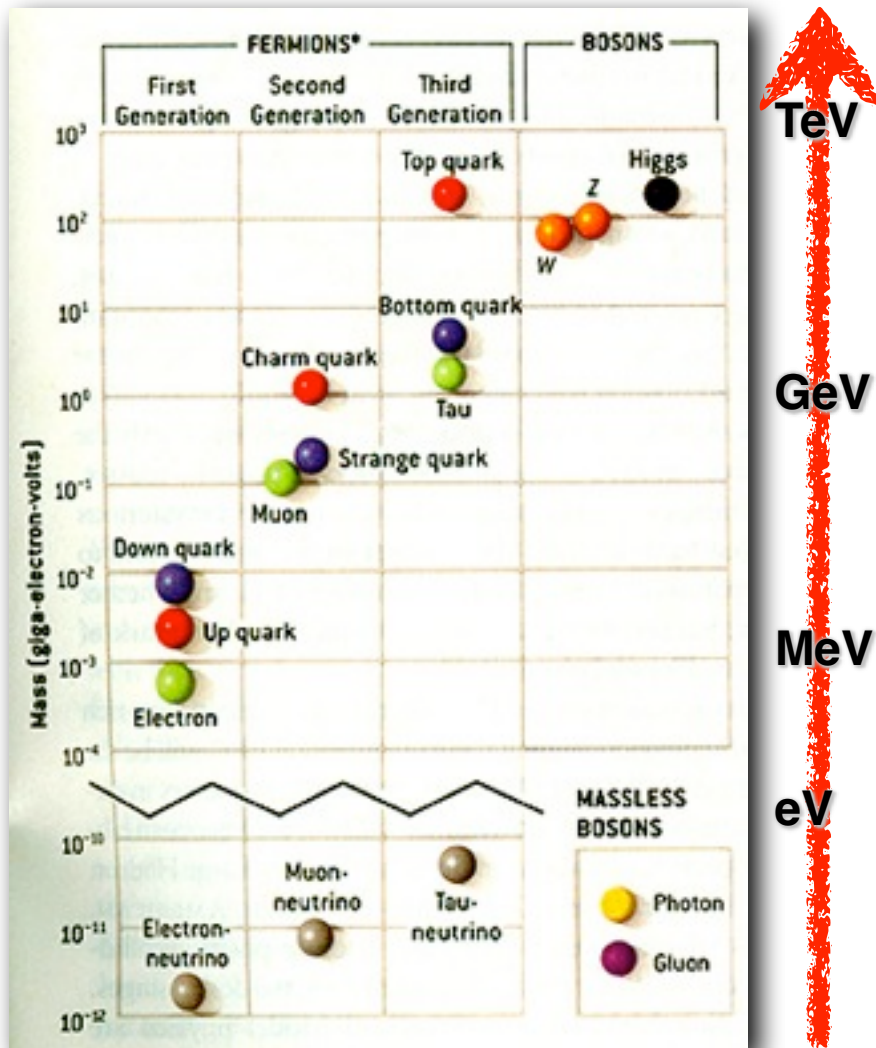
eV

Erler, Su (2013)



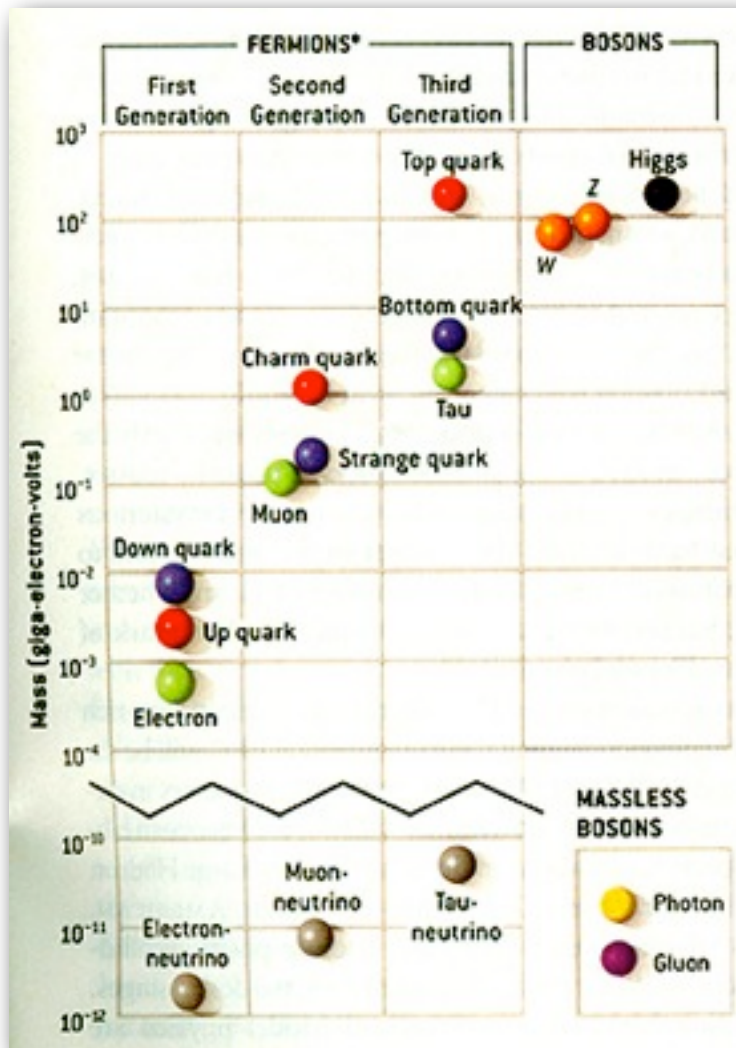
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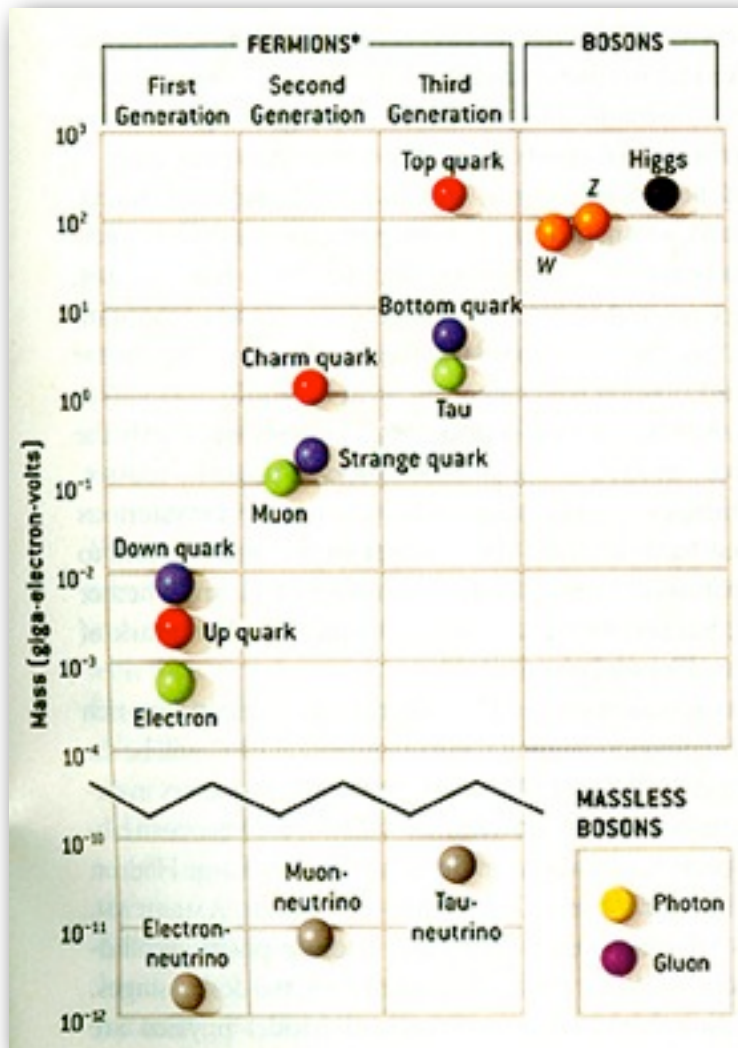


⊙ SM complete

valid up to Planck scale

Standard Model

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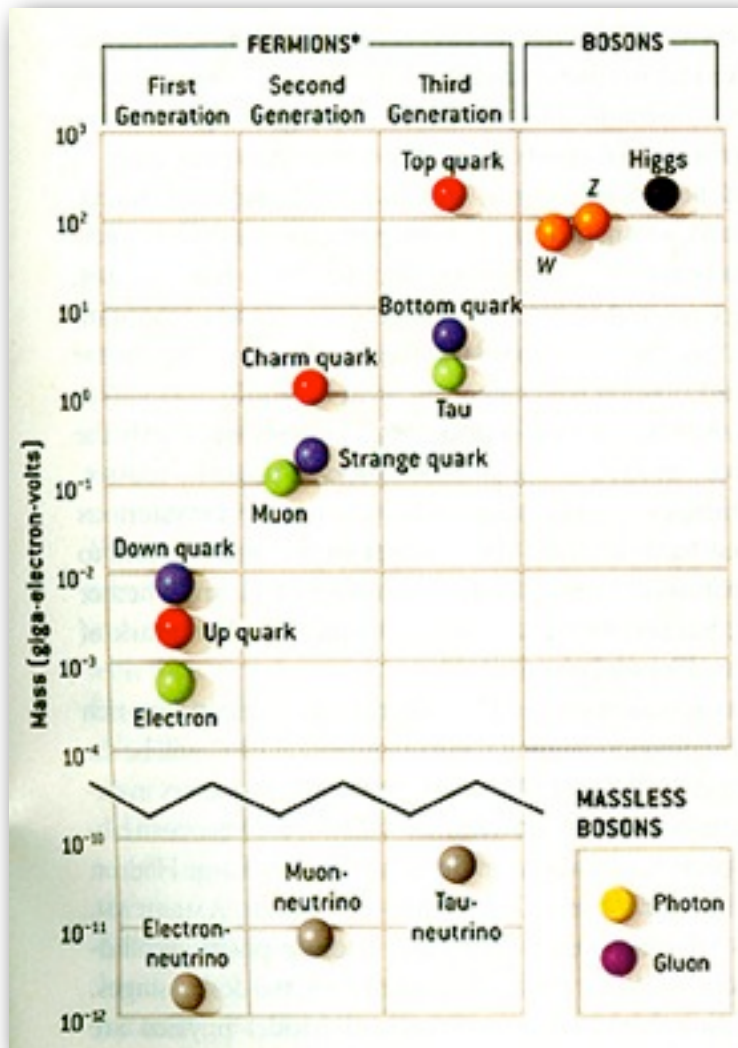
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TeV
GeV
MeV
eV

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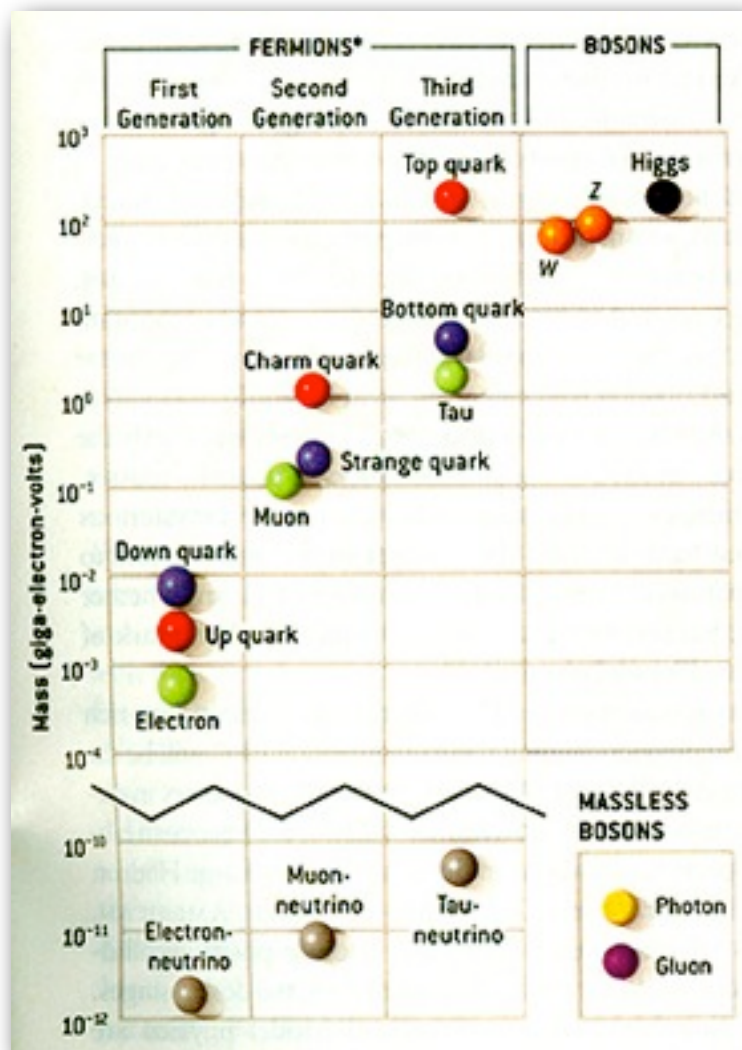
valid up to Planck scale

● Big questions

● Big ideas

Standard Model

Image credit: Gordon Kane, Scientific American, June 2003.



TeV

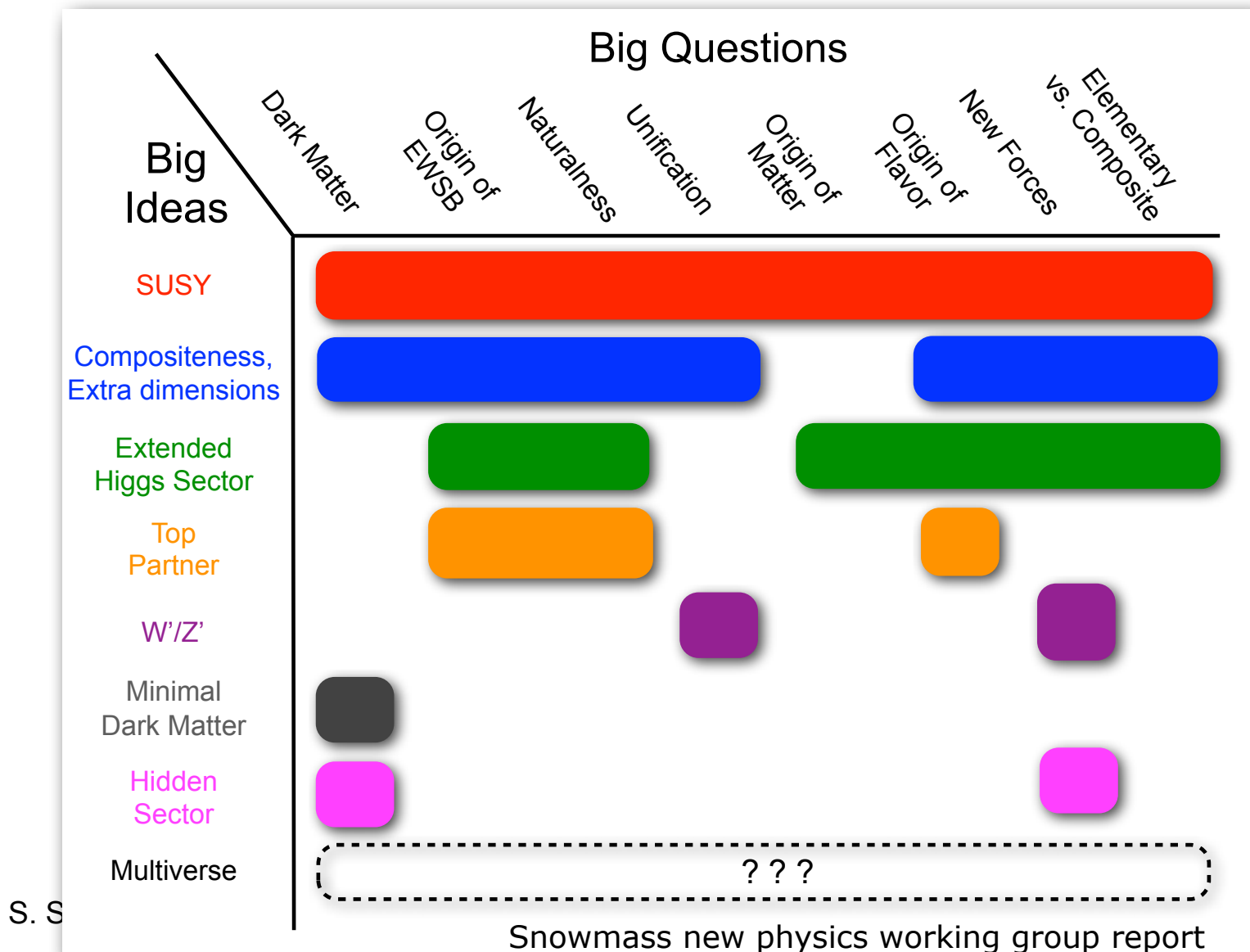
GeV

MeV

ev

- ⊙ SM complete
 - valid up to Planck scale
- ⊙ Big questions
- ⊙ Big ideas
- ⊙ unexpected...

New Physics beyond the SM



What did we learn from LHC 7/8 TeV ?

A Light Higgs is Puzzling...

- ◎ Light, weakly coupled boson: $m_h = 125\text{-}126\text{ GeV}$, $\Gamma < 1\text{ GeV}$
 - ➡ spin 0, a new kind of fundamental particle
 - ➡ Nothing protects its mass \Rightarrow New physics beyond the SM

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Then What? Still a lot of hard, but fun work to do!

A Light Higgs is Puzzling...

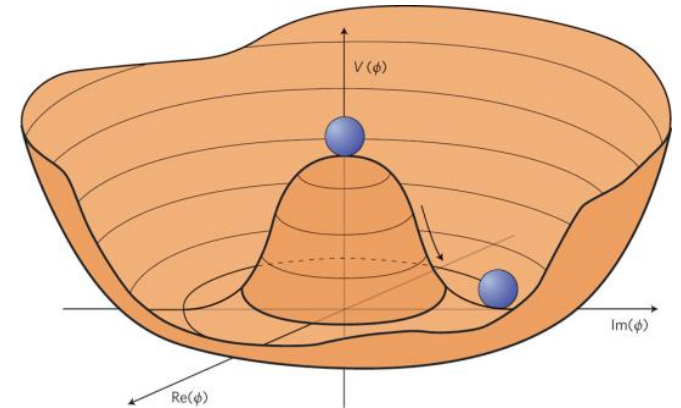
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Then What? Theoretically ...



$$V(\phi) = \frac{1}{2}\mu_h^2\phi^2 + \frac{\lambda}{4}\phi^4$$

$$\langle\phi\rangle \equiv v \neq 0 \quad \rightarrow \quad m_W = g_W \frac{v}{2}$$

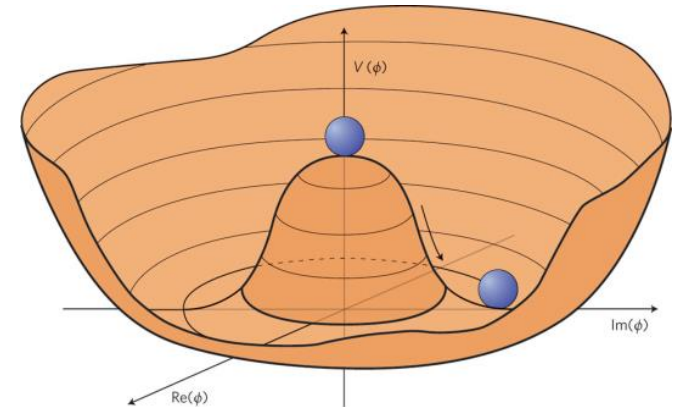
$$M_H^2 = -2\mu^2 = 2\lambda v^2$$

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At the verge of uncovering a deep theory

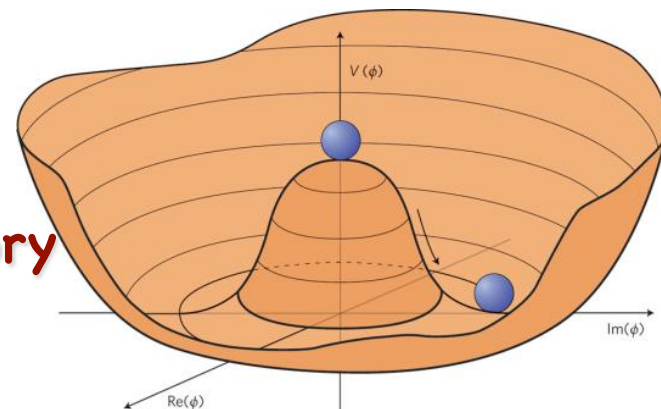
- λ determined by gauge couplings?

e.g., SUSY, $\lambda = (g_1^2 + g_2^2)/8$...

- or dynamically generated by a new strong force?

e.g., composite Higgs, Higgsless, extra dimensions, ...

S. Su



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Then What? experimentally...

© Is it a SM Higgs? Mass, width, spin, coupling, CP,...

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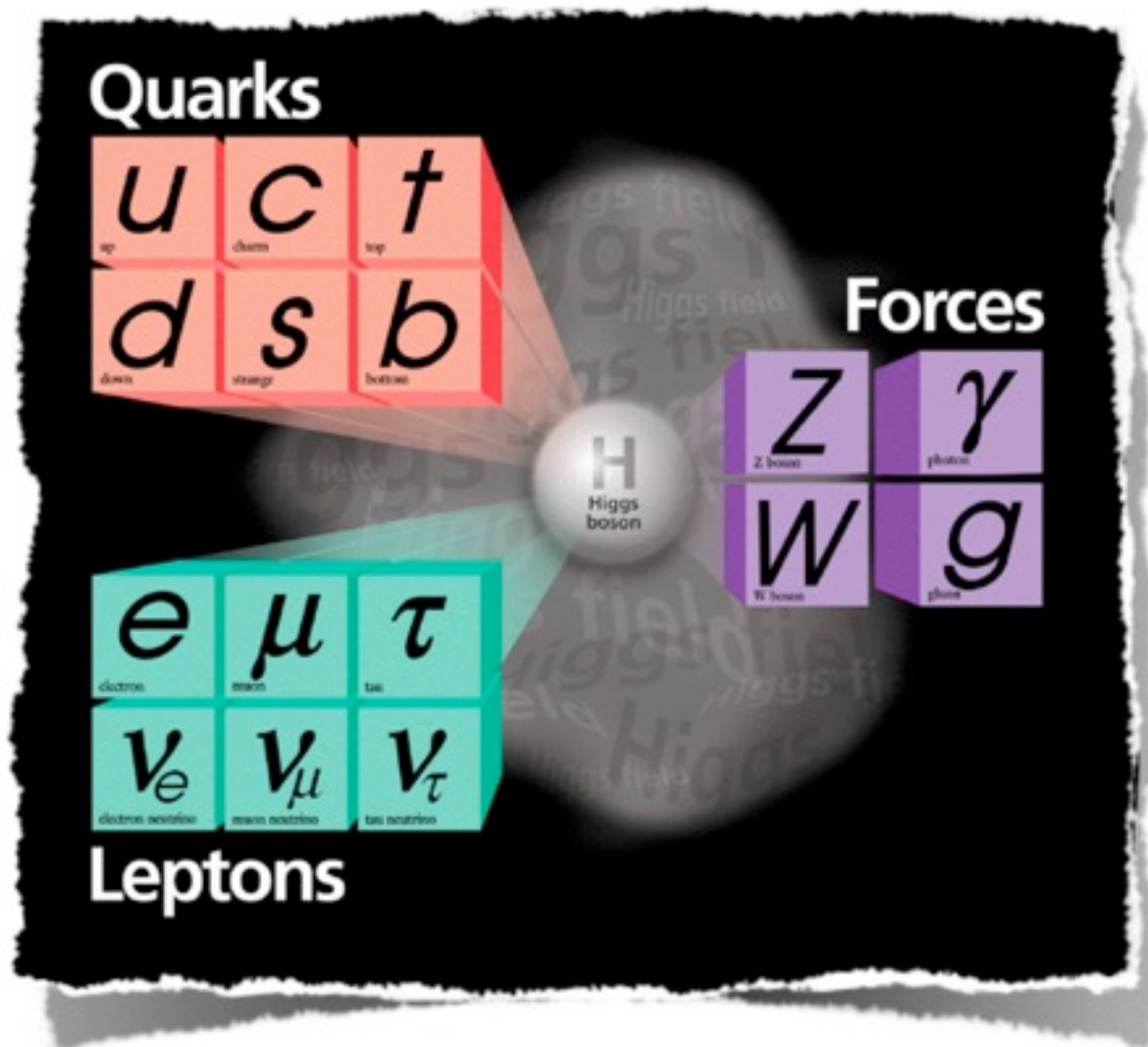
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syblings
 $H, A, H^\pm,$

...

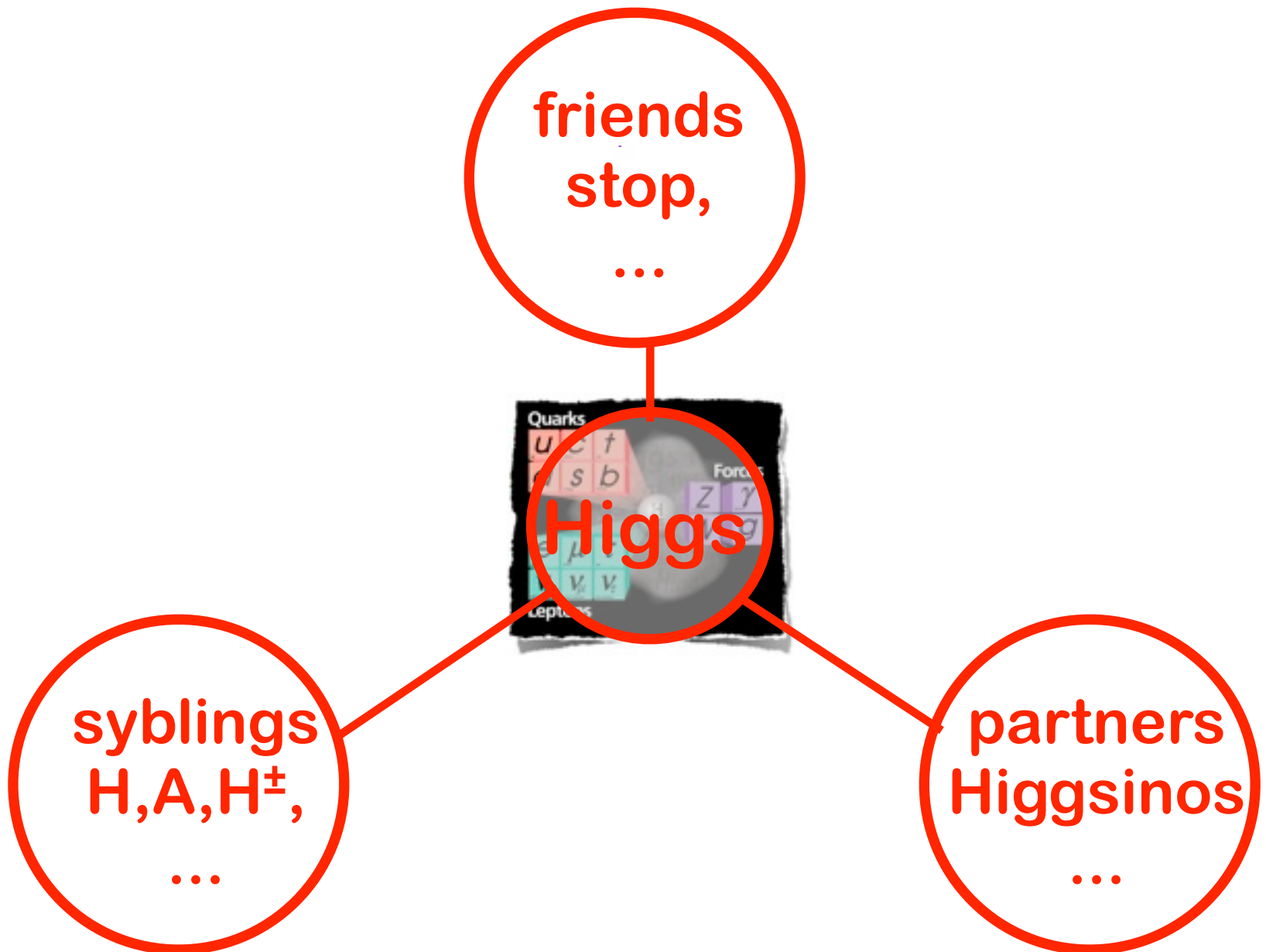


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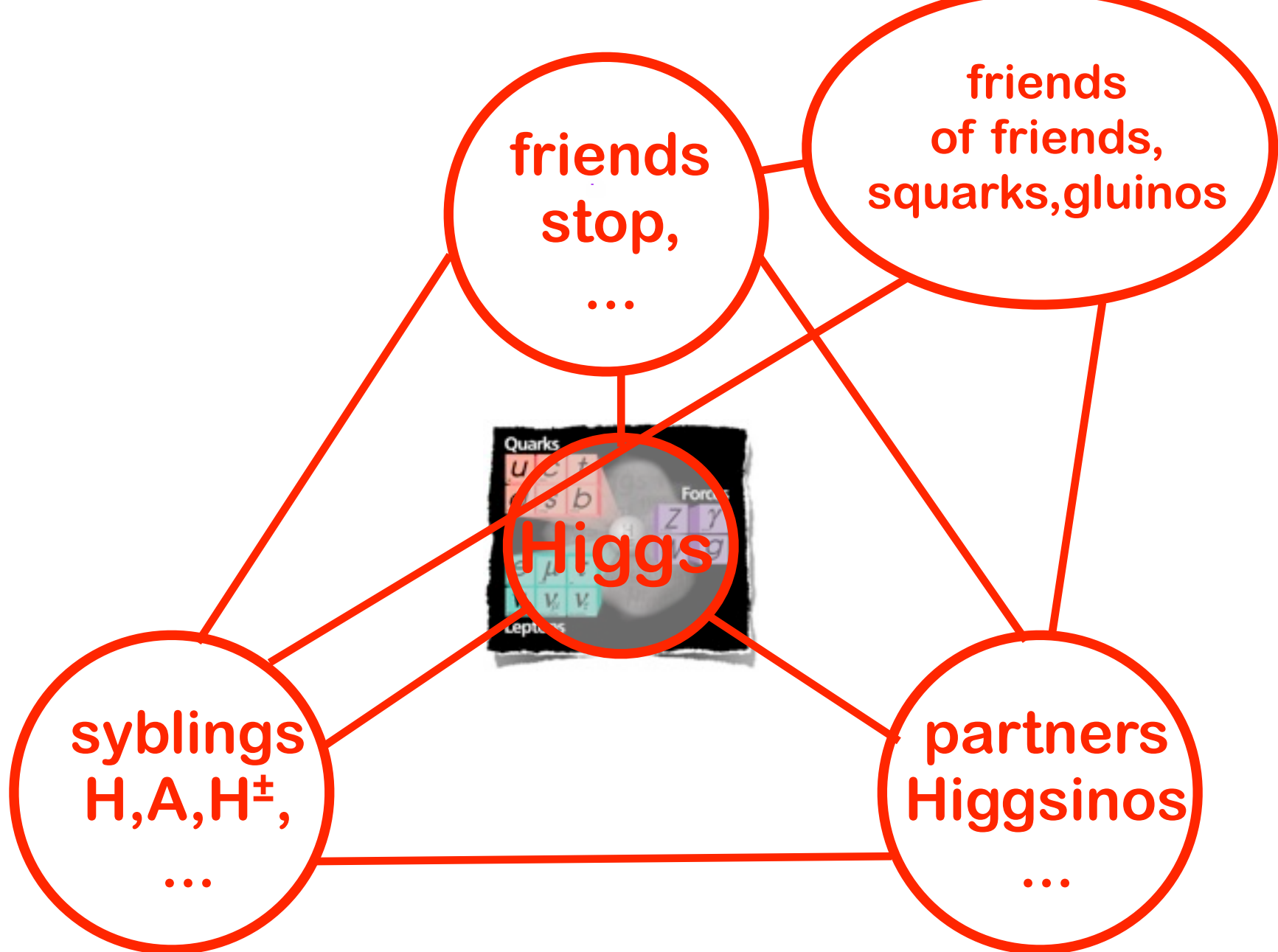
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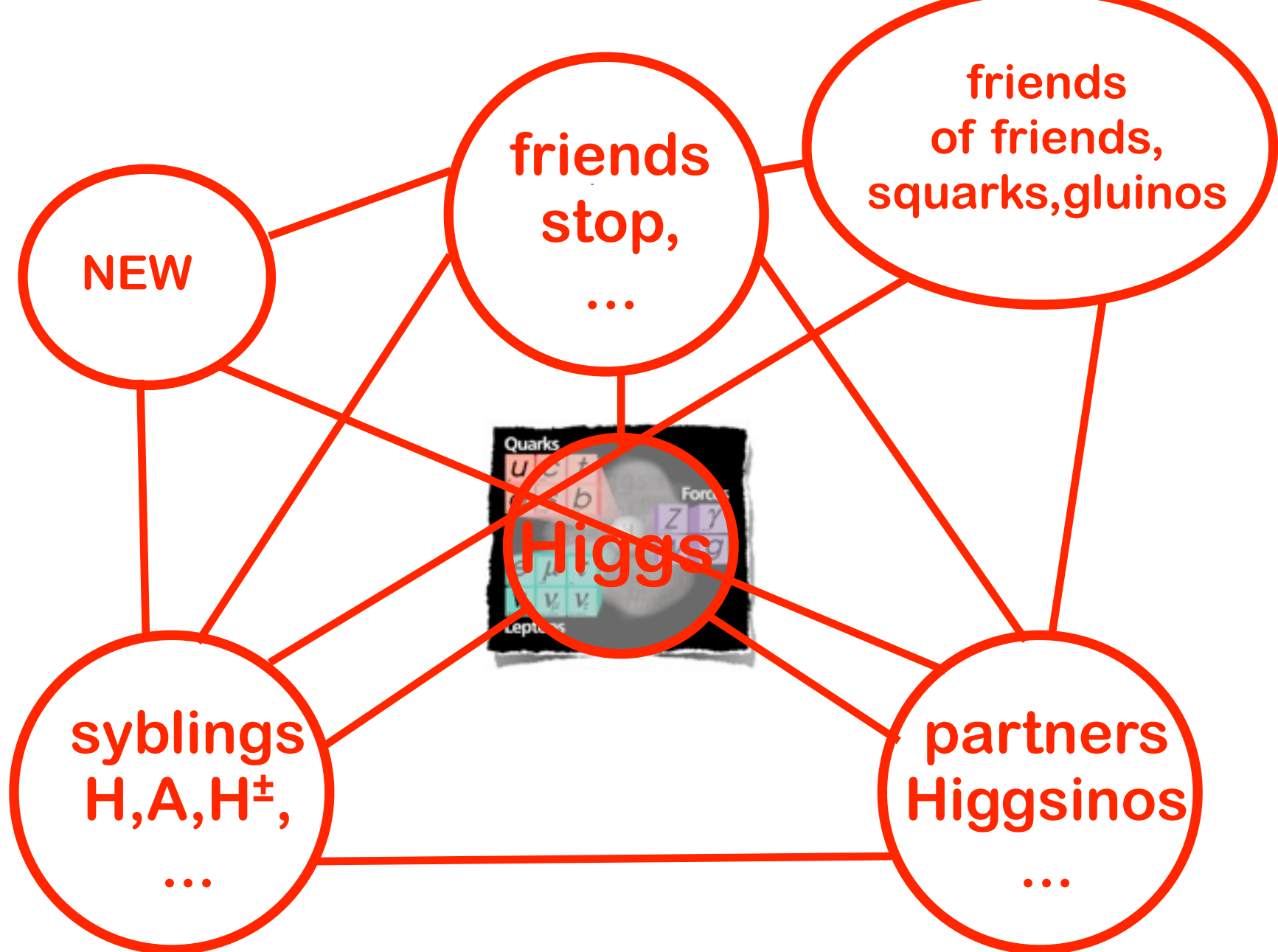
partners
Higgsinos

...









facebook

NEW

friends
stop,
...

friends
of friends,
squarks, gluinos

Higgs

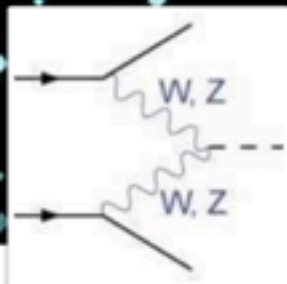
syblings
 $H, A, H^\pm,$
...

partners
Higgsinos



fac

OS



Higgs Boson

Add Friend

Message

...

Timeline

About

Photos

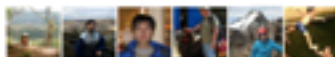
Friends 9 Mutual

More

About

To see what he shares with friends, [send him a friend request](#).

Add Friend



9 Mutual Friends

Work and Education



CERN

Scalar elementary particle · Geneva, Switzerland · Jan 1980 to present



Fermi National Accelerator Laboratory



European Center for Nuclear Research



CERN

Places Lived



Geneva, Switzerland

Hometown

Basic Information

Birthday

September 29, 1954

Gender

Male

fac

Friends

Add Friend

All Friends Mutual Friends People You May Know Following

Search Friends



JoAnne Hewett

295 friends

✓ Friends



Kyle Cranmer

652 friends

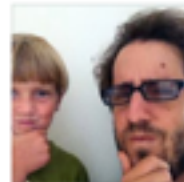
✓ Friends



Thomas G Rizzo

219 friends

✓ Friends



Daniel Whiteson

361 friends

✓ Friends



Carlos Wagner

601 friends

✓ Friends



Ann Nelson

72 mutual friends

✓ Friends



Jing Shu

1,401 friends

✓ Friends



John Conway

280 friends

✓ Friends



CERN

Basic Information

Birthday

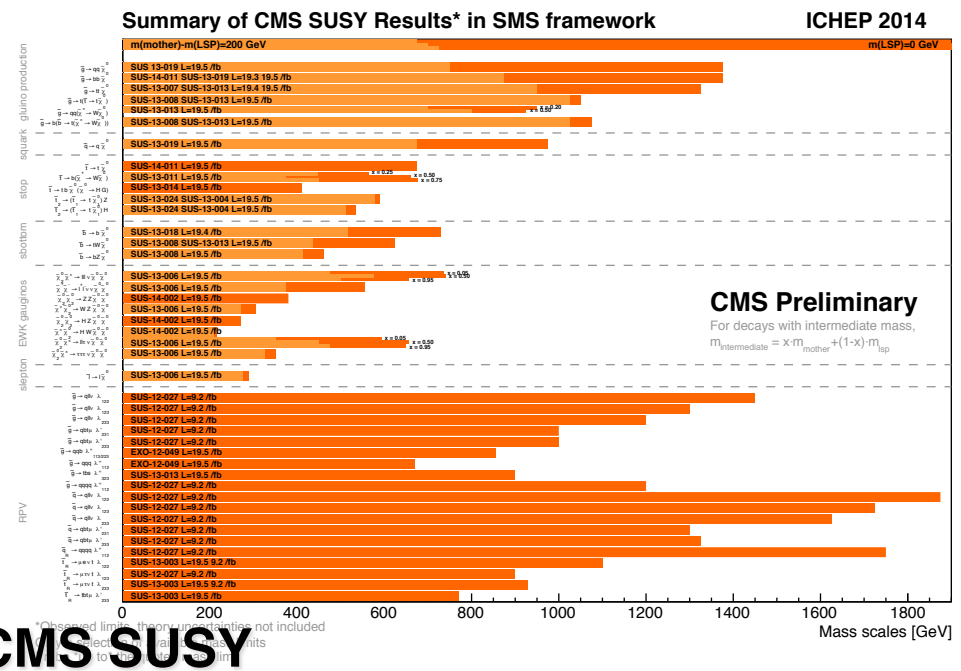
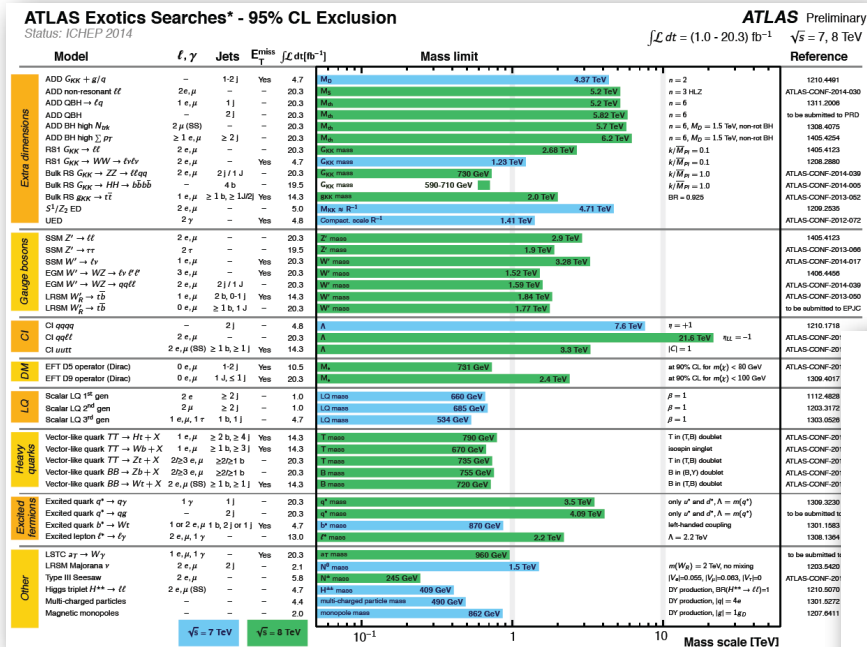
September 29, 1954

Gender

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New Physics Searches

© No new physics beyond the SM has been discovered yet



ATLAS exotic

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ATLAS Exotics Searches* - 95% CL
Status: ICHEP 2014

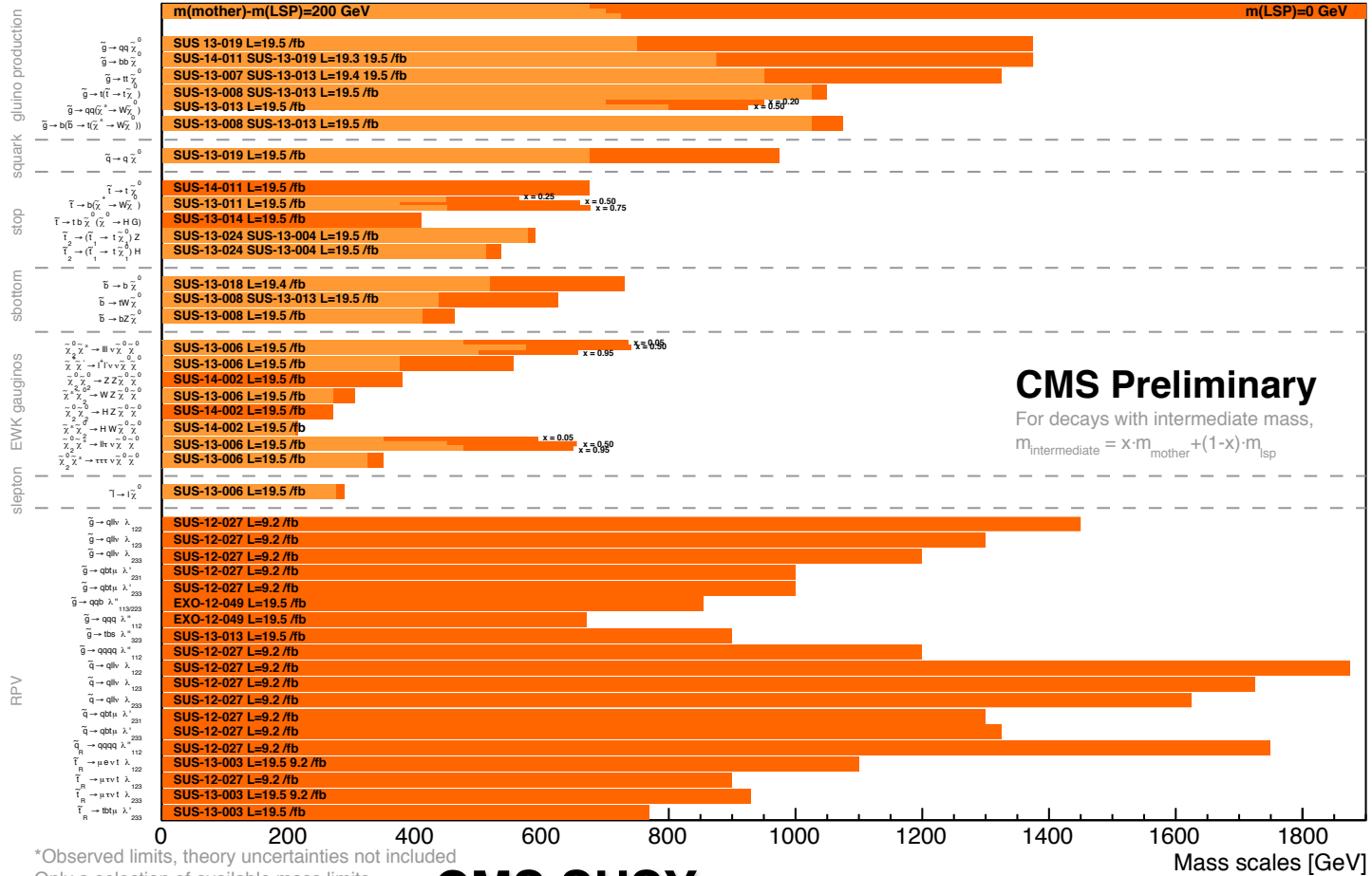
	Model	ℓ, γ	Jets	$E_{\text{miss}}^{\text{T}}$	$ \vec{c}_T /\text{TeV}$
Extra dimensions	ADD $Q_{\text{KK}} + q/\ell$	$2\mu, 1$	1-2	Yes	4.7
	ADD nonresonant $\ell\ell$	$2\mu, 1$	1	Yes	20.3
	ADD QRH + q/ℓ	$2\mu, 1$	1	Yes	20.3
	ADD QRH	$2\mu, 1$	1	Yes	20.3
	ADD RH high M_{KK}	≥ 1 (SR)	1	Yes	20.3
	ADD RH high \sqrt{s} , \sqrt{t}	$\geq 1.6\mu, \geq 2$	≥ 1	Yes	20.3
	RS1 $Q_{\text{KK}} + q/\ell$	$2\mu, 2$	1	Yes	20.3
	RS1 $Q_{\text{KK}} \rightarrow WW \rightarrow \ell\ell\gamma$	$2\mu, 2$	1	Yes	4.7
	Bulk RS $BB \rightarrow \ell\ell$	$2\mu, 2$	2/1/1	Yes	20.3
	Bulk RS $Q_{\text{KK}} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	$2\mu, 2$	4b	Yes	19.5
Gauge bosons	Bulk RS axion $\ell\ell \rightarrow \ell\ell$	$1\mu, \geq 1.5, 1.5\mu$	Yes	Yes	14.3
	$\mathcal{L}(\text{UED})$	2γ	Yes	Yes	4.8
CI	SSM $ZZ \rightarrow \ell\ell$	$2\mu, 2$	1	Yes	20.3
	SSM $ZZ \rightarrow \tau\tau$	2τ	1	Yes	19.5
	SSM $W^+W^- \rightarrow \ell\ell$	$2\mu, 2$	1	Yes	20.3
	SSM $W^+W^- \rightarrow \ell\ell\tau$	$2\mu, 2$	3b	Yes	20.3
	EGM $W^+W^- \rightarrow q\ell\ell$	$2\mu, 2$	2/1/1	Yes	20.3
DM	LRSM $W_2 \rightarrow \ell\ell$	$1\mu, 2b, 1\gamma$	Yes	Yes	14.3
	LRSM $W_2^0 \rightarrow \ell\ell$	$2\mu, 2$	1, 1, 1	Yes	20.3
	CI open	$2\mu, 2$	2	Yes	4.8
	CI $q\ell\ell$	$2\mu, 2$	1	Yes	20.3
	CI UED	$2\mu, 2$ (SR) $\geq 1b, 1\gamma$	Yes	Yes	14.3
LQ	EFT D5 operator (Dirac)	$2\mu, 1$	1-2	Yes	10.5
	EFT D5 operator (Dirac)	$2\mu, 1$	1, 4, 5, 1	Yes	20.3
	Scalar LQ 1 $^{\text{st}}$ gen	$2\mu, \geq 2$	1	Yes	10
	Scalar LQ 2 $^{\text{nd}}$ gen	$2\mu, \geq 2$	1	Yes	10
	Scalar LQ 3 $^{\text{rd}}$ gen	$1\mu, 1, 1$	1b, 1	Yes	4.7
Heavy quarks	Vector-like quark $TT \rightarrow Ht + X$	$2\mu, 2$ (SR) $\geq 2, \geq 4$	Yes	Yes	14.3
	Vector-like quark $TT \rightarrow Wb + X$	$2\mu, 2$ (SR) $\geq 1b, \geq 3$	Yes	Yes	14.3
	Vector-like quark $TT \rightarrow Zt + X$	$2b\bar{b}, 2\mu, 2$	$\geq 2b, 1$	Yes	20.3
	Vector-like quark $BB \rightarrow Zb + X$	$2b\bar{b}, 2\mu, 2$	$\geq 2b, 1$	Yes	20.3
	Vector-like quark $BB \rightarrow Wt + X$	$2\mu, 2$ (SR) $\geq 1b, \geq 1$	Yes	Yes	14.3
Exotic fermions	Excited quark $q\ell \rightarrow q\gamma$	$1\mu, 1$	1	Yes	20.3
	Excited quark $q\ell \rightarrow q\gamma$	$1\mu, 2$ (SR) ≥ 2	Yes	Yes	4.7
	Excited lepton $\ell\ell \rightarrow \ell\ell$	$1\mu, 2, 1\gamma$	1, 2, 1	Yes	4.7
	Excited lepton $\ell\ell \rightarrow q\gamma$	$1\mu, 2, 1\gamma$	1	Yes	13.0
	Excited lepton $\ell\ell \rightarrow q\gamma$	$1\mu, 1, 1$	1	Yes	4.7
Other	LS10 $p \rightarrow \ell\ell$	$1\mu, 1, 1$	Yes	Yes	20.3
	LRSM Majorana ν	$2\mu, 2$	1	Yes	2.1
	Type III charged fermion	$2\mu, 2$	1	Yes	5.8
	Higgs triplet $HH \rightarrow \ell\ell$	$2\mu, 2$ (SR)	1	Yes	4.7
	Majorana ν + particles	$2\mu, 2$	1	Yes	4.7
Magnetic monopoles	Magnetic monopoles	$\sqrt{s} = 7\text{ TeV}$	$\sqrt{s} = 7\text{ TeV}$	Yes	2.0

ATLAS exoti

S. Su

Summary of CMS SUSY Results* in SMS framework

ICHEP 2014



*Observed limits, theory uncertainties not included

Only a selection of available mass limits
Probe *up to* the quoted mass limit

CMS SUSY

New Physics Searches

● No new physics beyond the SM has been discovered yet

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Bulk RS $G_{XX} \rightarrow WH \rightarrow \ell\ell b\bar{b}$	-	4b	-	19.5
Bulk RS $\text{stop} \rightarrow \ell\ell$	$1e, \mu$	$\geq 1b, \geq 1b\bar{b}$	Yes	14.3
S^1/Z_2 ED	$2e, \mu$	-	-	5.0
UED	2γ	-	Yes	4.8
Gauge bosons				
SSM $Z' \rightarrow \ell\ell$	$2e, \mu$	-	-	20.3
SSM $Z' \rightarrow \tau\tau$	$2e, \mu$	-	-	19.5
SSM $W' \rightarrow \ell\nu$	$1e, \mu$	-	Yes	20.3
EGM $W' \rightarrow WZ \rightarrow \ell\nu \ell\ell$	$3e, \mu$	-	Yes	20.3
EGM $W' \rightarrow WZ \rightarrow \ell\nu \ell\ell$	$2e, \mu$	2/1/1	-	20.3
LRSB $W'_\mu \rightarrow \ell\bar{\ell}$	$1e, \mu$	2b, 0-1	Yes	14.3
LRSB $W'_\mu \rightarrow \ell\bar{\ell}$	$0e, \mu$	$\geq 1b, 1\bar{b}$	-	20.3
CI				
CI $qqqq$	-	2	-	4.8
CI $qq\ell\ell$	$2e, \mu$	-	-	20.3
CI $uvt\ell$	$2e, \mu$ (SS) $\geq 1b, \geq 1\bar{b}$	Yes	-	14.3
DM				
EFT D5 operator (Dirac)	$0e, \mu$	1-2	Yes	10.5
EFT D9 operator (Dirac)	$0e, \mu$	1, 1-2, 3	Yes	20.3
LO				
Scalar LQ 1 st gen	$2e, \mu$	≥ 2	-	1.0
Scalar LQ 2 nd gen	$2e, \mu$	≥ 2	-	1.0
Scalar LQ 3 rd gen	$1e, \mu, 1\tau$	1b, 1	-	4.7
Heavy quarks				
Vector-like quark $TT \rightarrow Ht + X$	$1e, \mu$	$\geq 2b, \geq 4$	Yes	14.3
Vector-like quark $TT \rightarrow Wb + X$	$1e, \mu$	$\geq 1b, \geq 3$	Yes	14.3
Vector-like quark $TT \rightarrow Zt + X$	$20.3e, \mu$	$\geq 2b, 1b$	-	20.3
Vector-like quark $BB \rightarrow Zb + X$	$20.3e, \mu$	$\geq 2b, 1b$	-	20.3
Vector-like quark $BB \rightarrow Wt + X$	$2e, \mu$ (SS) $\geq 1b, \geq 1\bar{b}$	Yes	-	14.3
Excited fermions				
Excited quark $q^* \rightarrow q\gamma$	1γ	1	-	20.3
Excited quark $q^* \rightarrow qg$	-	2	-	20.3
Excited quark $b^* \rightarrow Wt$	$1e, 2e, \mu, 1b, 2\ell$ or 1	Yes	-	4.7
Excited lepton $\ell^* \rightarrow \ell\gamma$	$2e, \mu, 1\gamma$	-	-	13.0
Other				
LSTC $\gamma\gamma \rightarrow W\gamma$	$1e, \mu, 1\gamma$	-	Yes	20.3
LRSB Majorana ν	$2e, \mu$	2	-	2.1
Type III Seesaw	$2e, \mu$	-	-	5.8
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2e, \mu$ (SS)	-	-	4.7
Multi-charged particles	-	-	-	4.4
Magnetic monopoles	-	-	-	2.0

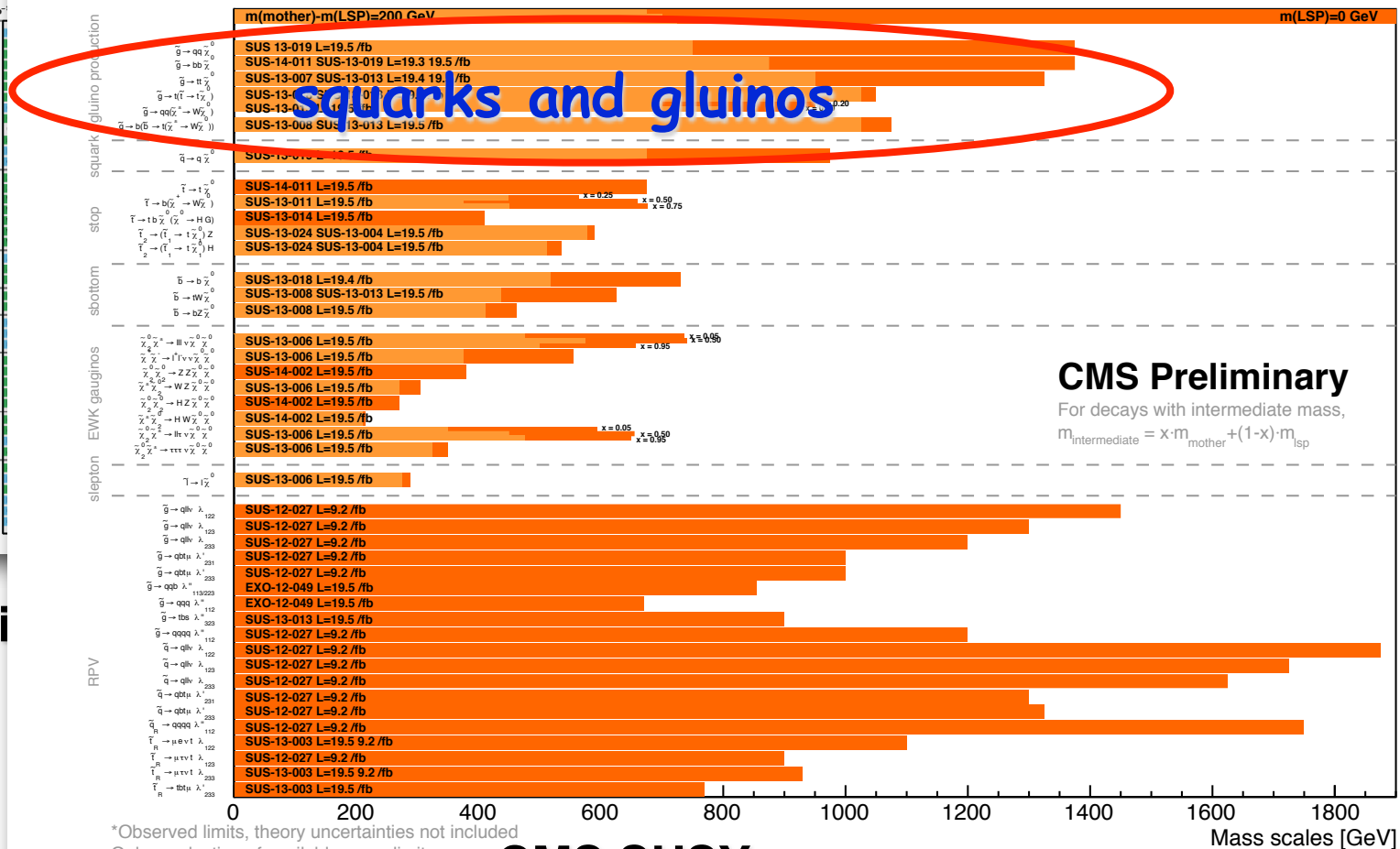
$\sqrt{s} = 7 \text{ TeV}$ $\sqrt{s} = 8 \text{ TeV}$

ATLAS exoti

S. Su

Summary of CMS SUSY Results* in SMS framework

ICHEP 2014



*Observed limits, theory uncertainties not included

Only a selection of available mass limits

Probe *up to* the quoted mass limit

New Physics Searches

● No new physics beyond the SM has been discovered yet

ATLAS Exotics Searches* - 95% CL
Status: ICHEP 2014

Model	ℓ, γ	Jets	E_{miss}	\sqrt{s} [TeV]
Extra dimensions				
ADD $G_{KK} + g/g$	-	1-2	Yes	4.7
ADD non-resonant $\ell\ell$	$2e, \mu$	1	-	20.3
ADD QSH $\rightarrow \ell\ell$	$1e, \mu$	1	-	20.3
ADD QSH	-	2	-	20.3
ADD BH high N_{jet}	$2e, \mu$ (SS)	-	-	20.3
ADD BH high Σp_T	$\geq 1e, \mu$	≥ 2	-	20.3
RS1 $G_{KK} \rightarrow \ell\ell$	$2e, \mu$	-	-	20.3
RS1 $G_{KK} \rightarrow WW \rightarrow \ell\nu\ell\nu$	$2e, \mu$	-	Yes	4.7
Bulk RS $G_{KK} \rightarrow ZZ \rightarrow \ell\ell\ell\ell$	$2e, \mu$	2/1/1	-	20.3
Bulk RS $G_{KK} \rightarrow WH \rightarrow \ell\ell b\bar{b}$	-	4b	-	19.5
Bulk RS $g_{KK} \rightarrow \ell\ell$	$1e, \mu$	$\geq 1b, \geq 1b\bar{b}$	Yes	14.3
S^1/Z_2 ED	$2e, \mu$	-	-	5.0
UED	2γ	-	Yes	4.8
Gauge bosons				
SSM $Z' \rightarrow \ell\ell$	$2e, \mu$	-	-	20.3
SSM $Z' \rightarrow \tau\tau$	$2e, \mu$	-	-	19.5
SSM $W' \rightarrow \ell\nu$	$1e, \mu$	-	Yes	20.3
EGM $W' \rightarrow WZ \rightarrow \ell\nu\ell\ell$	$3e, \mu$	-	-	20.3
EGM $W' \rightarrow WZ \rightarrow \ell\nu\ell\ell$	$2e, \mu$	2/1/1	-	20.3
LRSB $W'_\mu \rightarrow \ell\bar{\nu}$	$1e, \mu$	2b, 0-1	Yes	14.3
LRSB $W'_\mu \rightarrow \ell\bar{\nu}$	$0e, \mu$	$\geq 1b, 1\bar{b}$	-	20.3
CI				
CI $qqqq$	-	2	-	4.8
CI $qq\ell\ell$	$2e, \mu$	-	-	20.3
CI $qq\ell\ell$	$2e, \mu$ (SS) $\geq 1b, \geq 1\bar{b}$	Yes	-	14.3
DM				
EFT D5 operator (Dirac)	$0e, \mu$	1-2	Yes	10.5
EFT D5 operator (Dirac)	$0e, \mu$	1, 4, 5, 1	Yes	20.3
LQ				
Scalar LQ 1 st gen	$2e, \mu$	≥ 2	-	1.0
Scalar LQ 2 nd gen	$2e, \mu$	≥ 2	-	1.0
Scalar LQ 3 rd gen	$1e, \mu, 1\tau$	1b, 1	-	4.7
Heavy quarks				
Vector-like quark $TT \rightarrow Ht + X$	$1e, \mu$	$\geq 2b, \geq 4$	Yes	14.3
Vector-like quark $TT \rightarrow Wb + X$	$1e, \mu$	$\geq 1b, \geq 3$	Yes	14.3
Vector-like quark $TT \rightarrow Zt + X$	$2e, \mu$	$\geq 2b, \geq 2$	-	20.3
Vector-like quark $BB \rightarrow Zt + X$	$2e, \mu$	$\geq 2b, \geq 2$	-	20.3
Vector-like quark $BB \rightarrow Wt + X$	$2e, \mu$ (SS) $\geq 1b, \geq 1\bar{b}$	Yes	-	14.3
Excited fermions				
Excited quark $q^* \rightarrow q\gamma$	1γ	1	-	20.3
Excited quark $q^* \rightarrow qg$	-	2	-	20.3
Excited quark $b^* \rightarrow Wt$	$1e, 2e, \mu, 1b, 2\bar{b}$ or 1τ	Yes	-	4.7
Excited lepton $\ell^* \rightarrow \ell\gamma$	$2e, \mu, 1\gamma$	-	-	13.0
Other				
LSTC $\gamma\gamma \rightarrow W\gamma$	$1e, \mu, 1\gamma$	-	Yes	20.3
LRSB Majorana ν	$2e, \mu$	2	-	2.1
Type III Seesaw	$2e, \mu$	-	-	5.8
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2e, \mu$ (SS)	-	-	4.7
Multi-charged particles	-	-	-	4.4
Magnetic monopoles	-	-	-	2.0

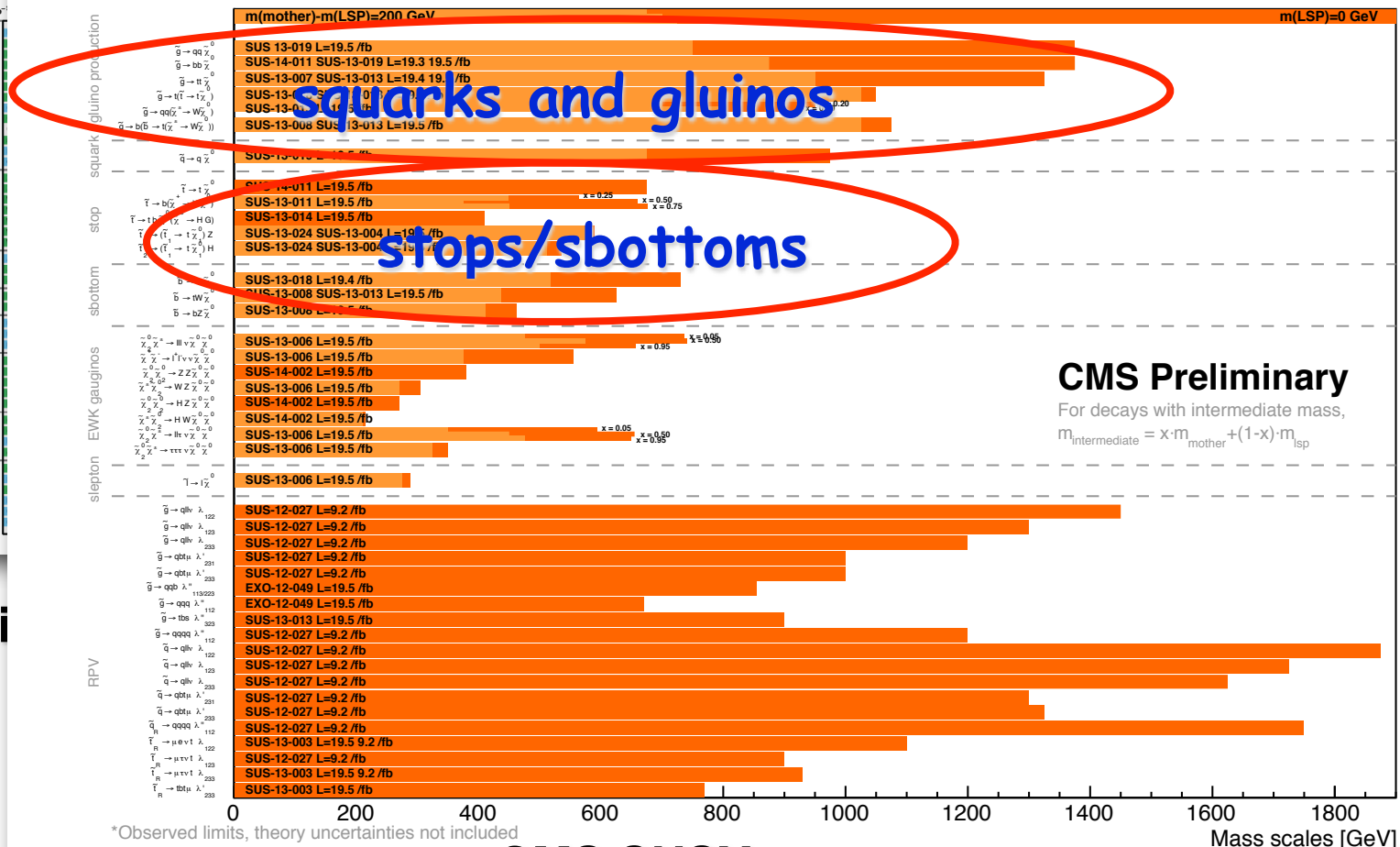
$\sqrt{s} = 7$ TeV $\sqrt{s} = 8$ TeV

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ICHEP 2014



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Probe *up to* the quoted mass limit

New Physics Searches

© No new physics beyond the SM has been discovered yet

ATLAS Exotics Searches* - 95% CL						
Status: ICHIEP 2014						
	Model	ℓ, γ	Jets	Emits	\sqrt{s} (TeV)	
Extra dimensions	ADD GRS $\ell\ell + q$			1-2 j	Yes	47
	ADD non-resonant $\ell\ell$	2 e, μ			Yes	20.3
	ADD GRH $\ell\ell + q$	2 e, μ	1 j		Yes	20.3
	ADD GRH $\ell\ell$	2 e, μ	2 j		Yes	20.3
	ADD BH $H_{\text{eff}} N_{\text{eff}}$	2 μ (88)			Yes	20.3
	ADD BH $H_{\text{eff}} \gamma$	$\geq 1 e, \mu$	$\geq 2 j$		Yes	20.3
	R81 GRS $\ell\ell$	2 e, μ			Yes	20.3
	R81 GRS $\ell\ell + WW + t\bar{t}\nu$	2 e, μ		Yes	47	
	Bulk RS GRS $\ell\ell + ZZ + t\bar{t}\nu$	2 e, μ	2 j/1 j		Yes	20.3
	Bulk RS GRS $\ell\ell + HH + b\bar{b}b$		4 b		Yes	14.5
Gauge bosons	Bulk RS GRS $\ell\ell + t\bar{t}$	2 e, μ	2, 1b, 2 j, $\geq 1 L_{\text{eff}}$		Yes	14.5
	$S/\lambda Z$				Yes	5.0
	UED	2 γ		Yes	4.8	
CI	SSM $2\tau \rightarrow \ell\ell$	2 e, μ			Yes	20.3
	SSM $2\tau \rightarrow \tau\tau$	2 τ			Yes	19.5
	SSM $W\ell \rightarrow W\ell + \nu\ell\ell$	2 e, μ		Yes	20.3	
	SSM $W\ell \rightarrow WZ + \nu\ell\ell$	3 e, μ		Yes	20.3	
	SSM $W\ell \rightarrow W\ell + \nu\ell\ell$	2 e, μ	2 j/1 j		Yes	20.3
DM	LRSM $W_2 \rightarrow \tau\bar{\tau}$	1 e, μ	2B, 0 j	Yes	14.3	
	LRSM $W_2 \rightarrow t\bar{t}$	0 e, μ	1B, 1 j	Yes	14.3	
LO	CI $\nu\nu\nu$	2 e, μ	2 j		Yes	48
	CI $\nu\nu\ell\ell$	2 e, μ	$\geq 2 j, \geq 1 j$		Yes	14.3
Heavy quarks	CI $u\bar{u}t\bar{t}$	2 e, μ (88)	$\geq 2 j, \geq 1 j$	Yes	14.3	
	CI $u\bar{u}t\bar{t}$	2 e, μ (88)	$\geq 2 j, \geq 1 j$	Yes	14.3	
Higgs boson	EFT D5 operator (Dirac)	0 e, μ	1-2 j	Yes	10.5	
	EFT D5 operator (Viral)	0 e, μ	1, $\leq 1.5 j$	Yes	20.3	
	Scalar GL^2 1 st gen	2 μ	$\geq 2 j$		Yes	20.3
	Scalar GL^2 2 nd gen	2 μ	$\geq 2 j$		Yes	20.3
	Vector-like quark $7T \rightarrow Hb + X$	1 e, μ	1, 1 b, 1 j		Yes	4.7
Higgs boson	Vector-like quark $7T \rightarrow H + X$	1 e, μ	2 b, $\geq 4 j$	Yes	14.3	
	Vector-like quark $7T \rightarrow Wb + X$	1 e, μ	2 b, $\geq 3 j$	Yes	4.7	
	Vector-like quark $7T \rightarrow Z\tau + X$	$2\bar{2} 3 e, \mu$	$\geq 2\bar{2} 1 b$	Yes	20.3	
	Vector-like quark $6B \rightarrow Zb + X$	$2\bar{2} 3 e, \mu$	$\geq 2\bar{2} 1 b$	Yes	20.3	
	Vector-like quark $6B \rightarrow Wt + X$	2 e, μ (88)	$\geq 1 b, \geq 1 j$	Yes	14.3	
Exotic fermions	Excited quark $q \rightarrow \gamma q$	1 γ	1 j		Yes	20.3
	Excited quark $q \rightarrow \gamma q$	1 γ	2 j		Yes	20.3
	Excited quark $q \rightarrow Wt$	1 $\mu, 2 e, 1 b, 2 j$ or 1 γ	Yes	4.7		
	Excited lepton $\ell \rightarrow \gamma \ell$	1 γ	1 j		Yes	13.0
	Excited lepton $\ell \rightarrow \gamma \ell$	1 γ	1 j		Yes	13.0
Higgs boson	LRHC $2\tau \rightarrow W\gamma$	1 e, μ, γ		Yes	20.3	
	LRHC Majorana ν	2 e, μ	2 j		Yes	2.1
	Type I Higgs ν	2 e, μ	2 j		Yes	5.8
	Higgs triplet $H_{\text{eff}} + \ell\ell$	2 e, μ (88)			Yes	4.7
	Multi-charged particles				Yes	4.7
Higgs boson	Magnetic monopoles				Yes	2.0
					Yes	2.0

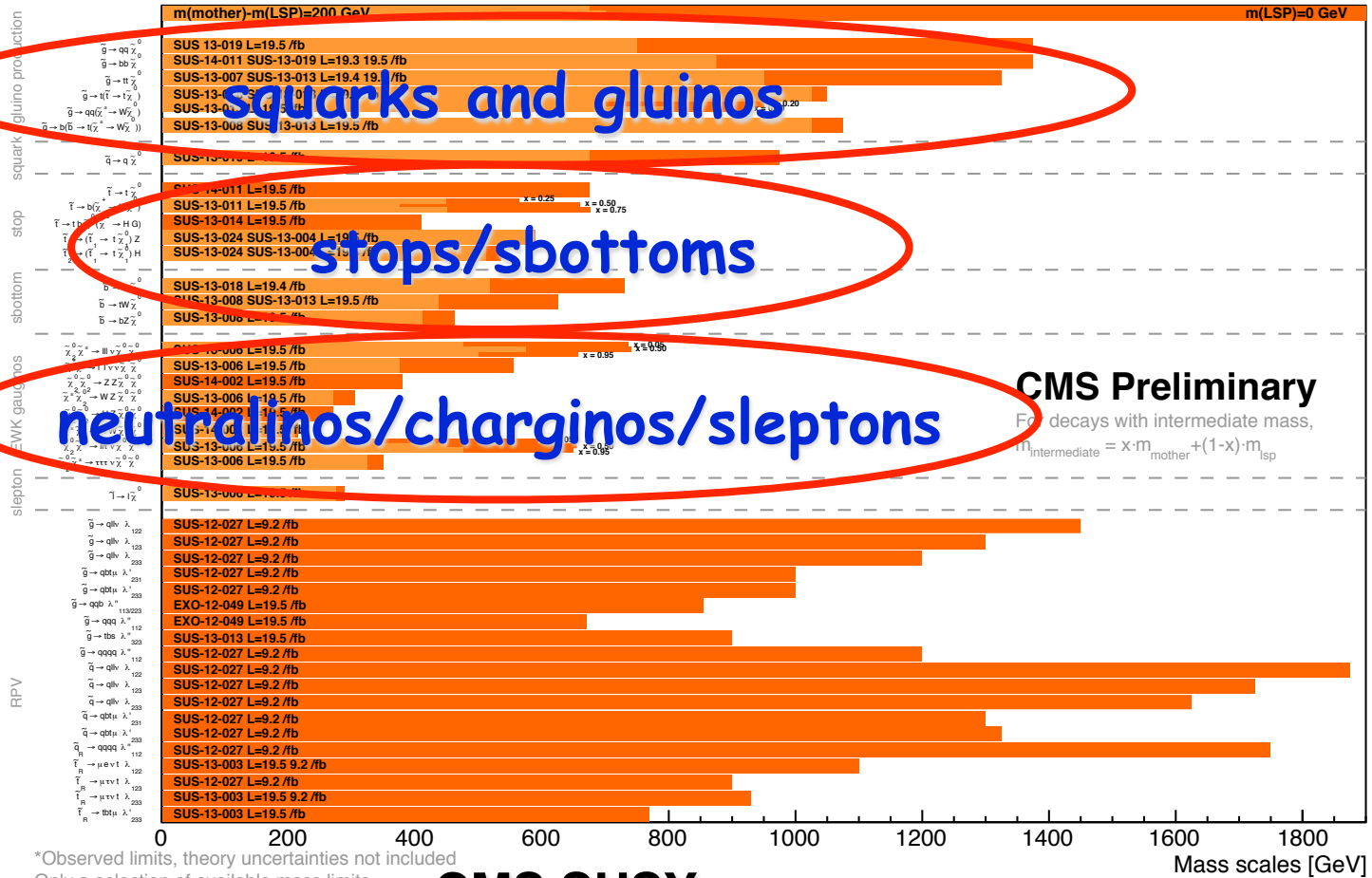
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CMS SUSY

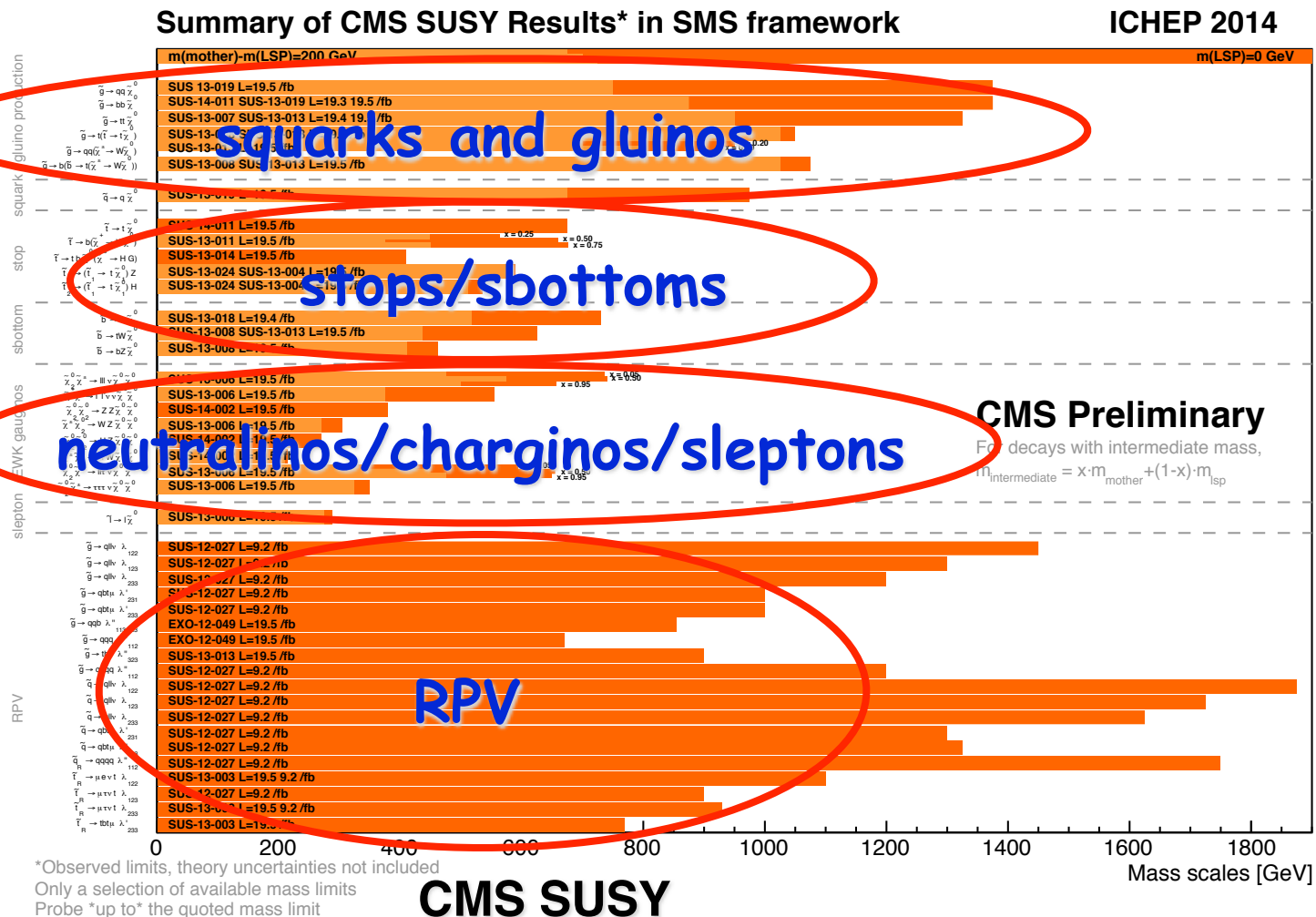
New Physics Searches

© No new physics beyond the SM has been discovered yet

ATLAS Exotics Searches* - 95% CL						
Status: ICHF 2014						
	Model	ℓ, γ	Jets	E_{miss}^{ℓ}	$\ell, \ell\ell, \ell\ell\ell$	
Extra dimensions	ADD $G_5 + g/\ell$		—	1-2 j	Yes	4.7
	ADD non-resonant $\ell\ell$		$2e, \mu$	—	—	20.3
	ADD $G_{BH} \rightarrow \ell\ell$		$1e, \mu$	1 j	—	20.3
	ADD G_{BH}		$2e, \mu$	—	—	20.3
	ADD $BB \rightarrow H + W_{\pm}$		2μ (SS)	—	—	20.3
	ADD $BB \rightarrow H + \nu\bar{\nu}$		$\geq 1e, \mu$	≥ 2 j	—	20.3
	RSI $G_{BH} \rightarrow \ell\ell$		$2e, \mu$	—	—	20.3
	RSI $BB \rightarrow WW \rightarrow \ell\ell$		$2e, \mu$	—	—	4.7
	Bulk RS $G_{BH} \rightarrow ZZ \rightarrow \ell\ell$		$2e, \mu$	$2/1/1\gamma$	—	4.7
	Bulk RS $G_{BH} \rightarrow H\ell\ell$		$2e, \mu$	—	—	19.5
Bulk RS $BB \rightarrow \ell\ell$		$2e, \mu$	$\geq 1\ell, \geq 1\ell\gamma$	Yes	14.3	
S^2/Z ED		$2e, \mu$	—	—	5.0	
UED		2γ	—	Yes	4.8	
Gauge bosons	SSM $Z \rightarrow \ell\ell$		$2e, \mu$	—	—	20.3
	SSM $Z \rightarrow \tau\tau$		2τ	—	—	19.5
	SSM $W^+ \rightarrow \ell\ell$		$2e, \mu$	—	—	Yes 20.3
	SSM $W^+ \rightarrow WZ \rightarrow \ell\ell \nu\ell$		$2e, \mu$	—	—	Yes 20.3
	EGM $W^+ \rightarrow WZ \rightarrow \ell\ell \nu\ell$		$2e, \mu$	$2/1/1\gamma$	—	—
LRSM $W_2^+ \rightarrow \ell\ell$		$2e, \mu$	$2\ell, 0\ell, 1\ell$	Yes	14.3	
LRSM $W_2^+ \rightarrow \ell\bar{\nu}$		$2e, \mu$	$\geq 1\ell, 1\ell$	—	20.3	
CI	Ci open		$2e, \mu$	2 j	—	4.8
	Ci unit		$2e, \mu$ (SS)	$\geq 1\ell, \geq 1\ell$	Yes	14.3
DM	EFT D5 operator (Dirac)		$0e, \mu$	1-2 j	Yes	10.5
	EFT D5 operator (Scalar)		$0e, \mu$	$1, 4, 5, 1j$	Yes	20.3
LO	Scalar LO 1 st gen		$2e$	≥ 2 j	—	1.0
	Scalar LO 2 nd gen		2μ	≥ 2 j	—	1.0
	Scalar LO 3 rd gen		$1e, 1\mu, 1\tau$	$1\ell, 1\ell$	—	1.0
Heavy quarks	Vector-like quark $TT \rightarrow H + X$		$1e, \mu$	$\geq 2\ell, \geq 2\ell, 4j$	Yes	14.3
	Vector-like quark $BB \rightarrow W + X$		$2e, \mu$	$\geq 2\ell, \geq 2\ell, 2j$	Yes	14.3
	Vector-like quark $TT \rightarrow Z + X$		$2e, \mu$	$\geq 2\ell, \geq 2\ell, 2j$	Yes	14.3
	Vector-like quark $BB \rightarrow Z + X$		$2e, \mu$	$\geq 2\ell, \geq 2\ell, 2j$	Yes	14.3
	Vector-like quark $BB \rightarrow W + X$		$2e, \mu$	$\geq 2\ell, \geq 2\ell, 2j$	Yes	14.3
Exotic fermions	Excluded quark $q^* \rightarrow \ell\ell$		1γ	1 j	—	20.3
	Excluded quark $q^* \rightarrow \ell\ell + W$		$1e, 2e, 1\mu, 2/2/1\gamma$	—	—	4.7
	Excluded lepton $\ell^* \rightarrow \ell\ell$		$2e, 1\mu, 1\tau$	—	—	13.0
Other	LRSB $q\bar{q} \rightarrow W\gamma$		$1e, 1\mu, 1\tau$	—	—	Yes 20.3
	LRSM Majorana ν		$2e, \mu$	2 j	—	—
	Type I seesaw		$2e, \mu$	—	—	5.8
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$		$2e, \mu$ (SS)	—	—	4.7
	Multi-charged particles		$2e, \mu$	—	—	4.4
	Magnetic monopoles		$2e, \mu$	—	—	2.0
		$\sqrt{s} = 7$ TeV		$\sqrt{s} = 0$ TeV		

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S. Su



Then What?

Where is New Physics?

larger mass? Small Coupling? Too much BG?

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- © Direct search for new particles

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- © Direct search for new particles

Need colliders with larger energies (pp or e⁺e⁻ with large E_{cm})

Then What?

Where is New Physics?

larger mass? Small Coupling? Too much BG?

- ◎ Direct search for new particles

Need colliders with larger energies (pp or e+e- with large E_{cm})

- ◎ Indirect search for imprints on W, Z, top and Higgs

Then What?

Where is New Physics?

larger mass? Small Coupling? Too much BG?

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Need colliders with larger energies (**pp** or e^+e^- with large E_{cm})

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Need colliders/measurements with unprecedented accuracy

Then What?

Where is New Physics?

larger mass? Small Coupling? Too much BG?

- ◎ Direct search for new particles

Need colliders with larger energies (pp or e+e- with large E_{cm})

- ◎ Indirect search for imprints on W, Z, top and Higgs

Need colliders/measurements with unprecedented accuracy

(e+e- or pp with high luminosity)

Machine Options

China plans super collider

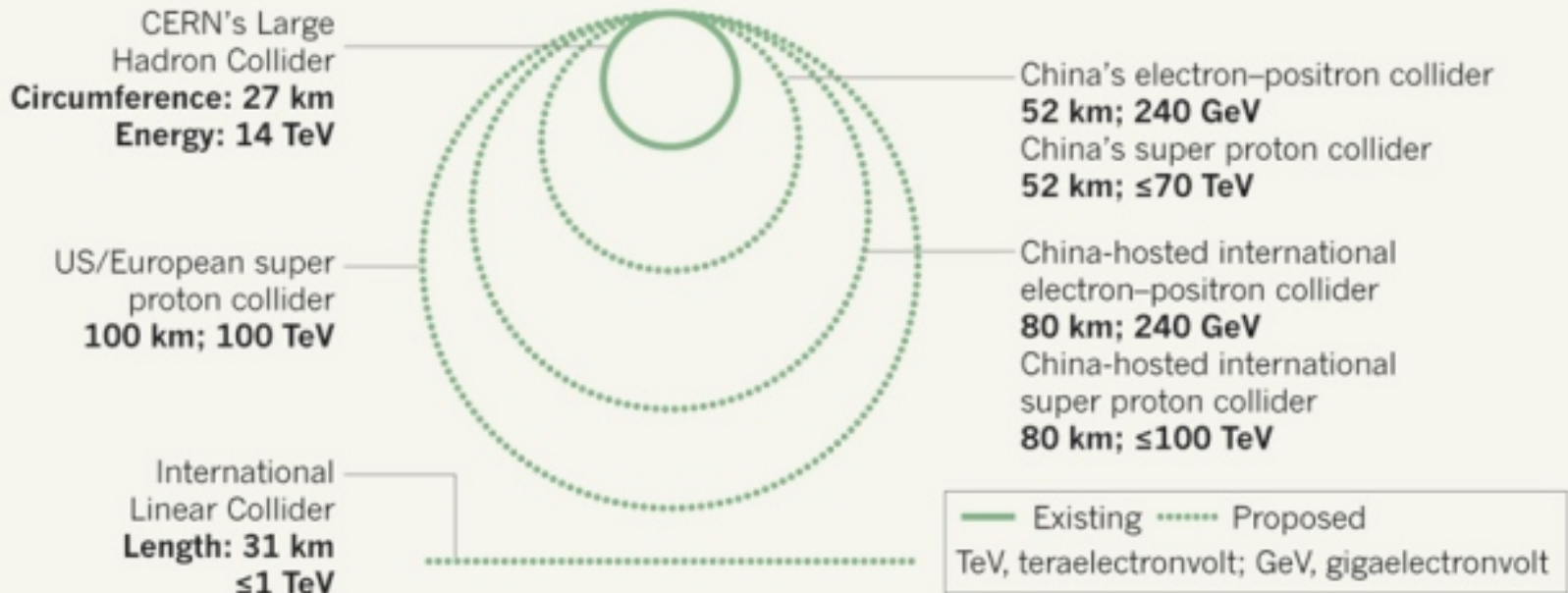
Nature News, July

Proposals for two accelerators could see country become collider capital of the world.

Elizabeth Gibney

COLLISION COURSE

Particle physicists around the world are designing colliders that are much larger in size than the Large Hadron Collider at CERN, Europe's particle-physics laboratory.



Physics opportunity for HL-LHC

14 TeV with 3 ab⁻¹

Physics opportunity for HL-LHC

14 TeV with 3 ab-1

- ◎ EW Physics

m_t , m_W , rare top decay, VVV/VVVV couplings, WW scattering, ...

- ◎ Higgs Physics

mass, width, CP, coupling, rare decay, self-coupling

- ◎ New heavy particles

Physics opportunity at pp machine

80 - 100 TeV

Physics opportunity at pp machine

80 - 100 TeV

- ◎ new particles: a few TeV - 30 TeV, beyond LHC reach
- ◎ increased rate for sub-TeV particle: increased precision wrt LHC/ILC: Z, W, top,...
- ◎ rare process in sub-TeV mass range
- ◎ Higgs and EWSB: more Higgs couplings, WW scattering, Higgs self-coupling

Physics opportunity at pp machine

80 - 100 TeV

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- ◎ rare process in sub-TeV mass range
- ◎ Higgs and EWSB: more Higgs couplings, WW scattering, Higgs self-coupling

SM Issues:

Parton distribution functions, Prof. Joey Huston (Michigan State University)

Top PDFs, Ahmed Ismail (ANL/UIC)

Study the SM-like Higgs

Study the SM-like Higgs

- ◎ Deviation of SM Higgs couplings
- ◎ New coupling structures, beyond the SM
- ◎ Higgs couples to new particles

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- ◎ Higgs couples to new particles

SM Higgs studies and couplings using 100 TeV collider

Ian Low (Northwestern Univ. and ANL)

Higgs related SUSY and BSM phenomena

Prof. Carlos Wagner (University of Chicago and ANL)

Di- and Triple-Higgs studies

Dr. Chien-Yi Chen (Brookhaven National Laboratory)

Higgs and SM Physics Highlights from the LHC

Jeffrey Berryhill (Fermilab)

Prospects of Higgs and SM measurements at HL-LHC

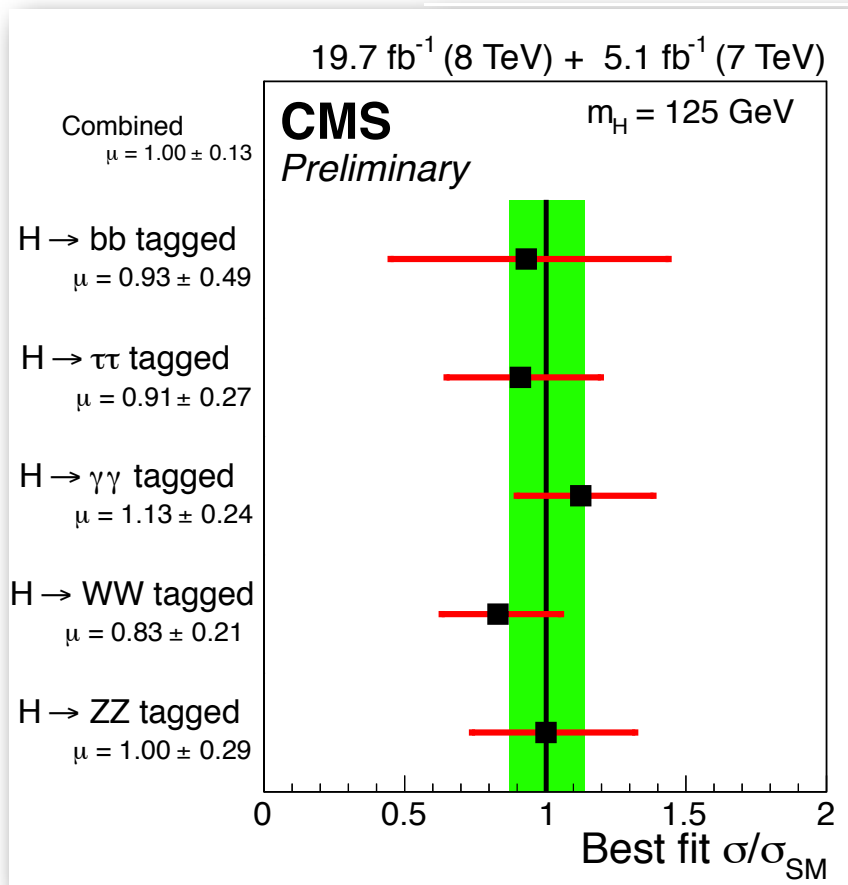
Hidetoshi Otono (Kyushu, Japan)

LHC (now): Higgs

Higgs and SM Physics Highlights from the LHC

Jeffrey Berryhill (Fermilab)

CMS-PAS-HIG-14-009



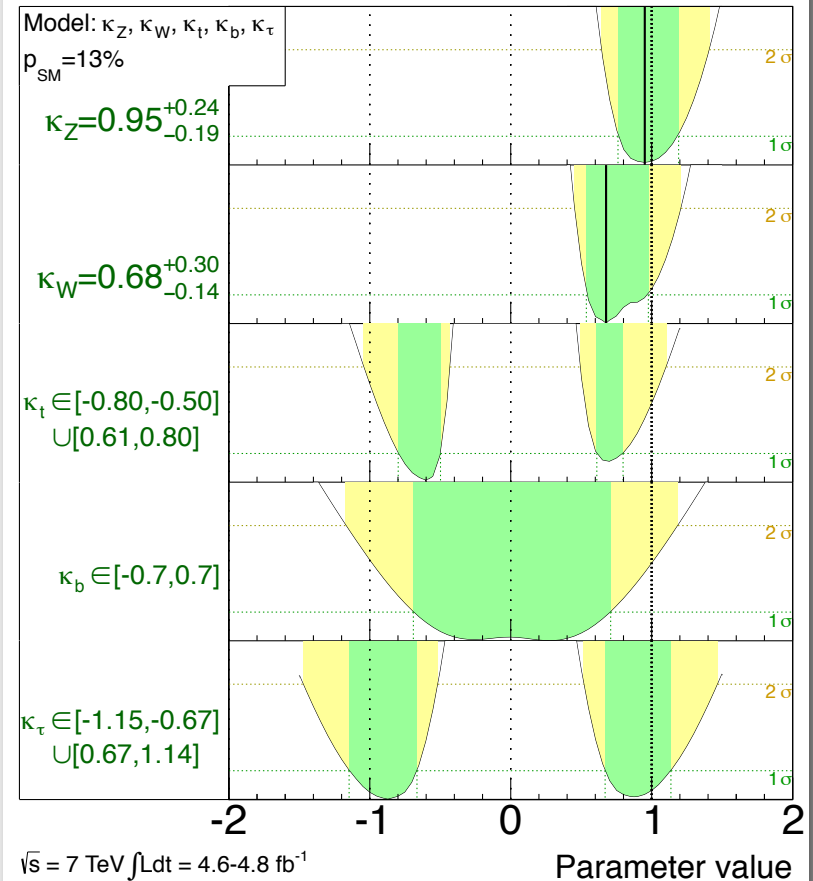
ATLAS-CONF-14-009

ATLAS Preliminary

$m_H = 125.5$ GeV

Total uncertainty

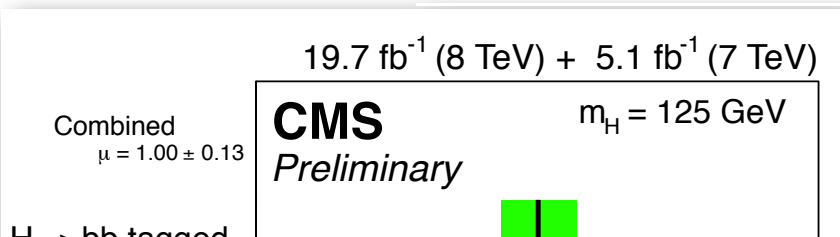
$\pm 1\sigma$ $\pm 2\sigma$



LHC (now): Higgs

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Jeffrey Berryhill (Fermilab)

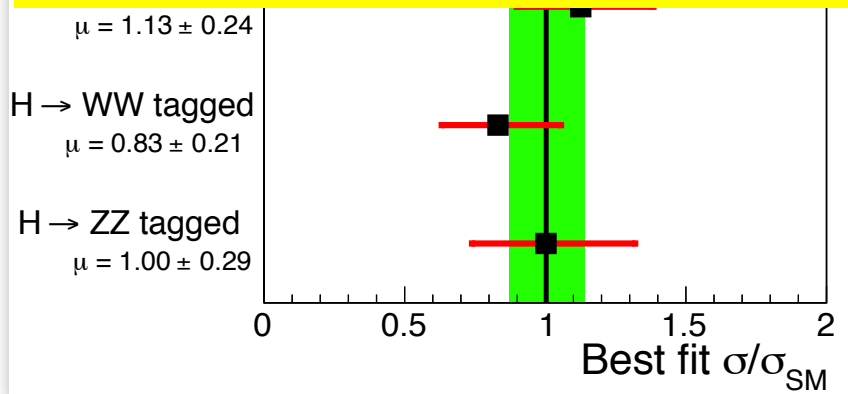
CMS-PAS-HIG-14-009



Higgs width: on-shell/off-shell ratio extracted from ZZ channel

CMS: $\Gamma_H < 22$ MeV (5.4 x SM)

ATLAS: $\Gamma_H < 20-32$ MeV (4.8-7.7 x SM)



ATLAS-CONF-14-009

ATLAS Preliminary

$m_H = 125.5$ GeV

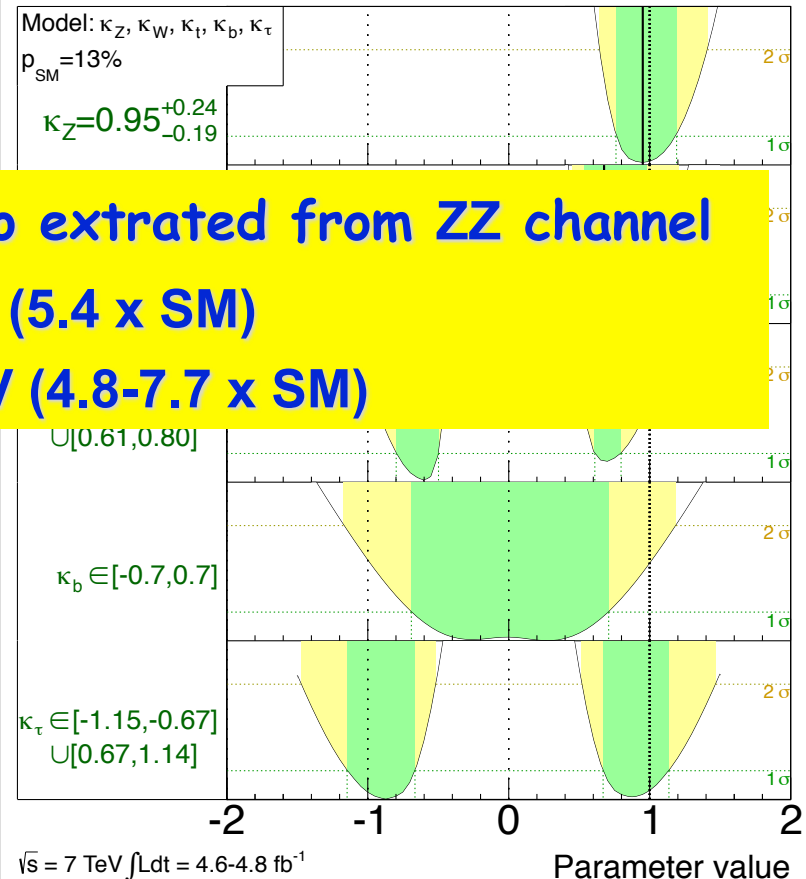
Total uncertainty

$\pm 1\sigma$ $\pm 2\sigma$

Model: $\kappa_Z, \kappa_W, \kappa_t, \kappa_b, \kappa_\tau$

$p_{SM} = 13\%$

$\kappa_Z = 0.95^{+0.24}_{-0.19}$



LHC, HL-LHC: Higgs

Prospects of Higgs and
SM measurements at HL-LHC
Hidetoshi Otono (Kyushu, Japan)

Higgs factory

- 170 M Higgs produced in each experiment, ~ 2 M events after selection
- rare decays: $\mu\mu$, $Z\gamma$, factor of 2 enhancement from 300 fb^{-1} to 3 ab^{-1}

Snowmass Higgs Working Group, 1310.8361

Luminosity	300 fb^{-1}	3000 fb^{-1}
Coupling parameter	7-parameter fit	
κ_γ	5 – 7%	2 – 5%
κ_g	6 – 8%	3 – 5%
κ_W	4 – 6%	2 – 5%
κ_Z	4 – 6%	2 – 4%
κ_u	14 – 15%	7 – 10%
κ_d	10 – 13%	4 – 7%
κ_ℓ	6 – 8%	2 – 5%
Γ_H	12 – 15%	5 – 8%

New physics contribution

$$\frac{\delta g_{\text{HXX}}}{g_{\text{HXX}}^{\text{SM}}} \leq 5\% \times \left(\frac{1 \text{ TeV}}{\Lambda} \right)^2$$

Model	κ_V	κ_b	κ_γ
Singlet Mixing	~ 6%	~ 6%	~ 6%
2HDM	~ 1%	~ 10%	~ 1%
Decoupling MSSM	~ -0.0013%	~ 1.6%	~ -0.4%
Composite	~ -3%	~ -(3 – 9)%	~ -9%
Top Partner	~ -2%	~ -2%	~ +1%

Factor of 1.5-2 better.

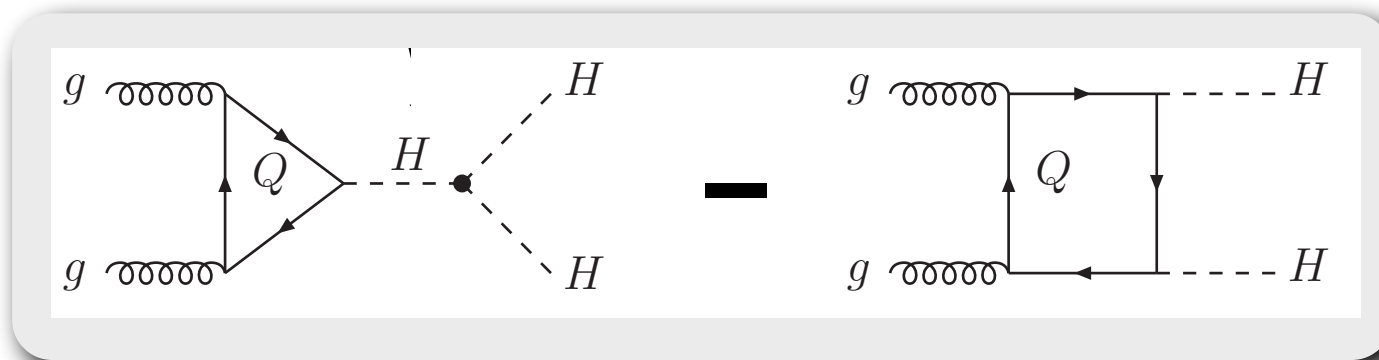
Might be good for some
new physics with scale < 1 TeV

S. Su

SM Higgs studies and couplings using 100 TeV collider
Ian Low (Argonne National Laboratory)

HL-LHC: Higgs self-coupling

Negative interference reduces the sensitivity to g_{HHH}



With 3 ab^{-1}

Expected events

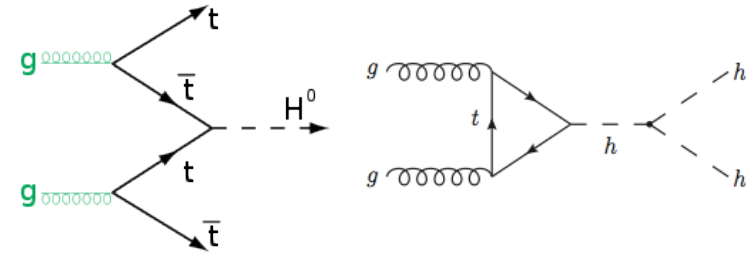
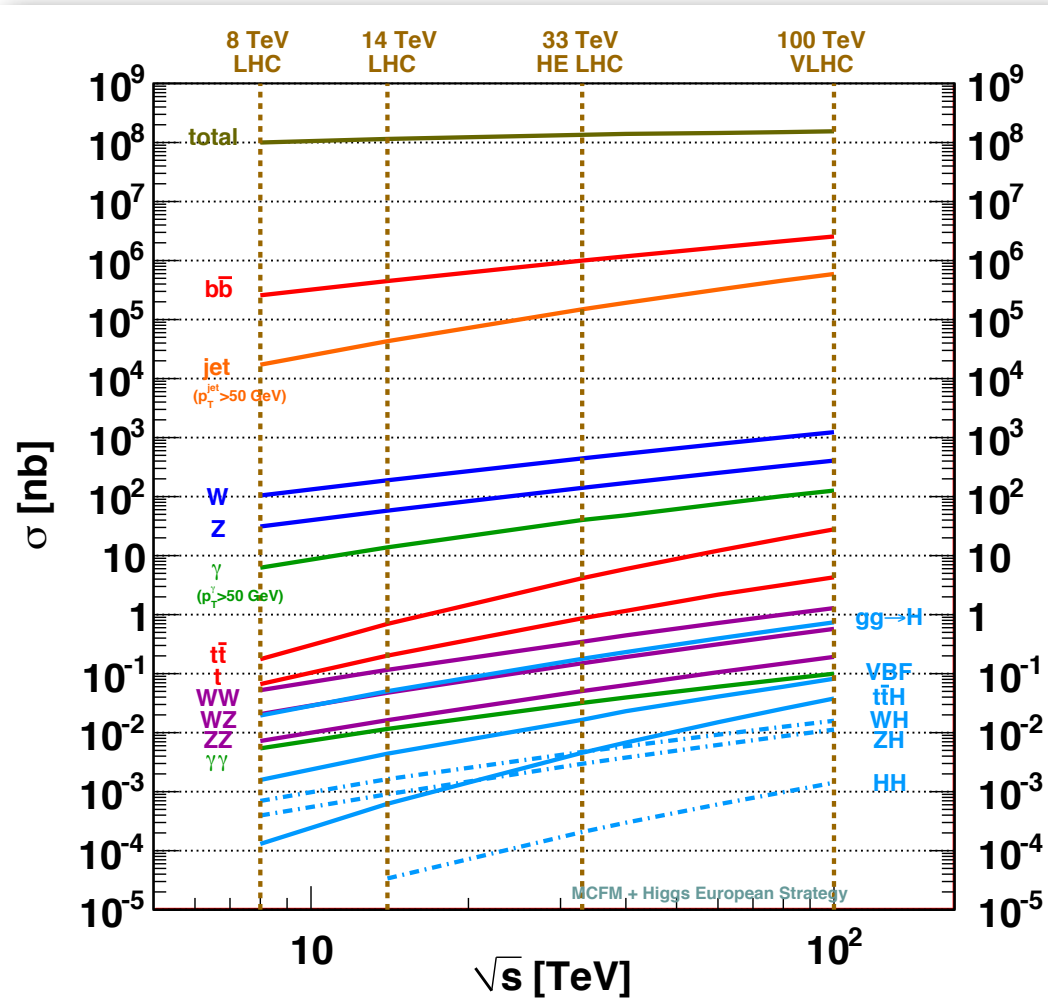
bbWW	30000
bb $\tau\tau$	9000
WWWW	6000
$\gamma\gamma$ bb	320
YYYY	1

- A sensitivity of 30-50% might be achieved for $bb\gamma\gamma$
- New physics deviation typically less than 20%

Di- and Triple-Higgs studies

Dr. Chien-Yi Chen (Brookhaven National Laboratory)

100 TeV pp: Higgs

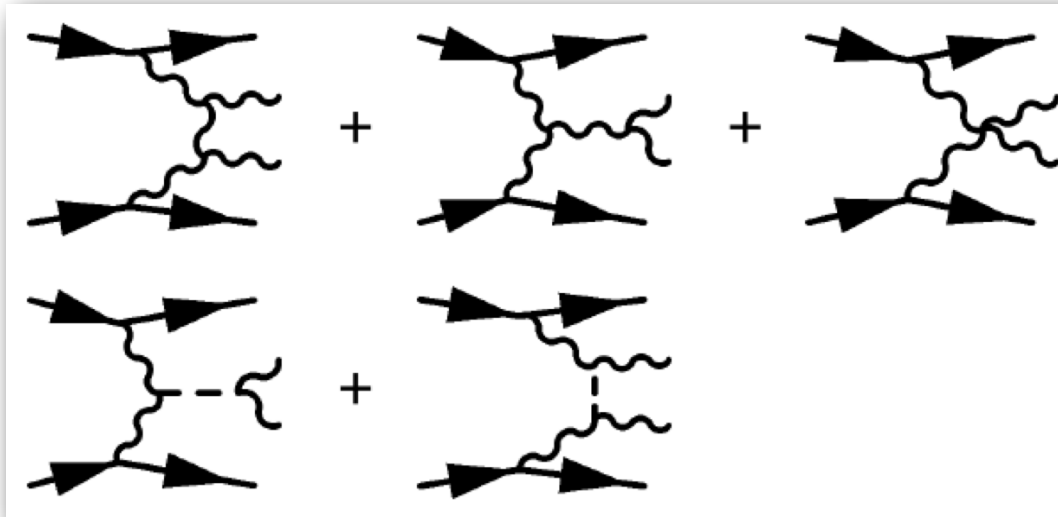


Process	σ (100 TeV)/ σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10 ³

λ_t : 1%

λ : 8%

WW scattering?



W_L W_L scattering and VBF Physics at 100 TeV Collider

Prof. Ashutosh Kotwal (Duke University)

Higgs and SM Physics Highlights from the LHC

Jeffrey Berryhill (Fermilab)

Prospects of Higgs and SM measurements at HL-LHC

Hidetoshi Otono (Kyushu, Japan)

Prospects of New Physics searches using HL-LHC

Altan Cakir (DESY)

BSM Higgs Sectors

BSM Higgs Sectors

- ◎ Implication of *SM*-like Higgs on BSM models
- ◎ Direct search for BSM Higgses

BSM Higgs Sectors

- ◎ Implication of SM-like Higgs on BSM models
- ◎ Direct search for BSM Higgses

Extended Higgs sector (other Higgs)

Dr. John Stupak (Purdue University Calumet)

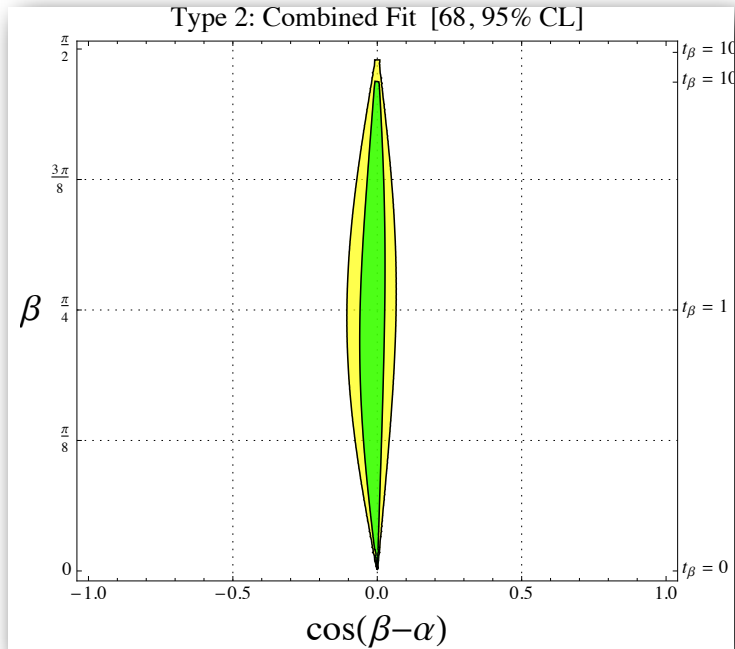
Higgs related SUSY and BSM phenomena

Prof. Carlos Wagner (University of Chicago and Argonne National Laboratory)

Prospects of Higgs and SM measurements at HL-LHC

Hidetoshi Otono (Kyushu, Japan)

LHC: H_{SM} implication on 2HDM



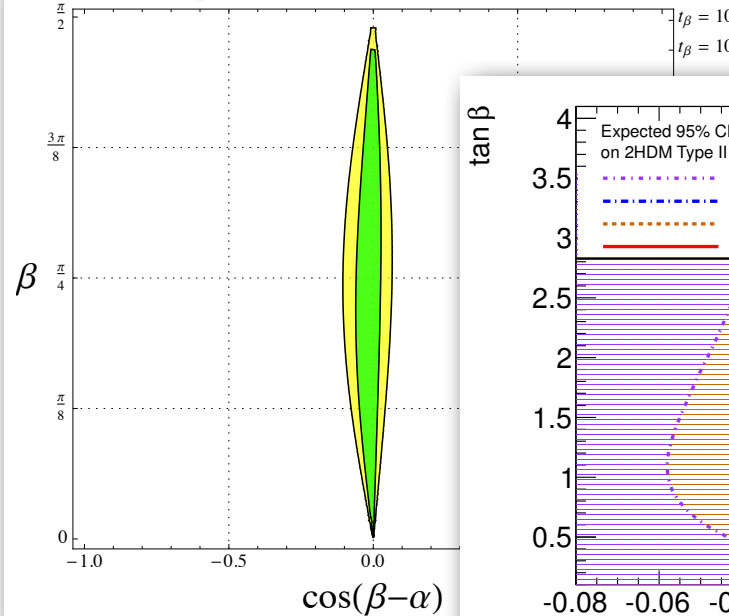
Craig, Galloway, Thomas, 1305.2424

Extended Higgs sector (other Higgs)

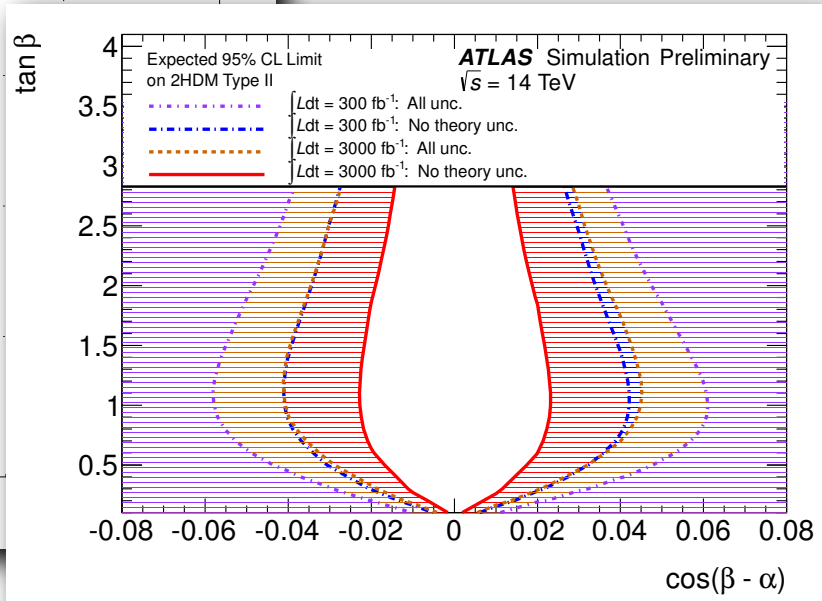
Dr. John Stupak (Purdue University Calumet)

LHC: H_{SM} implication on 2HDM

Type 2: Combined Fit [68, 95% CL]



ATLAS-PHYS-PUB-2013-015



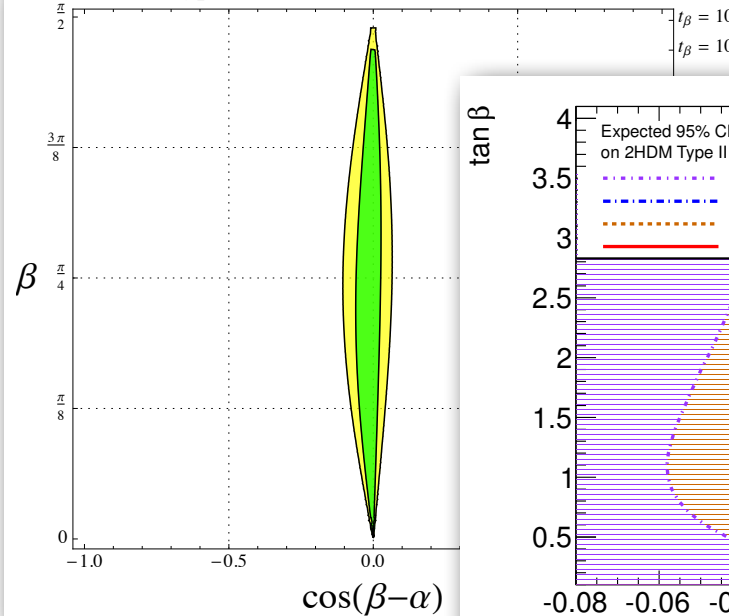
Craig, Galloway, Thomas, 1305.2424

Extended Higgs sector (other Higgs)

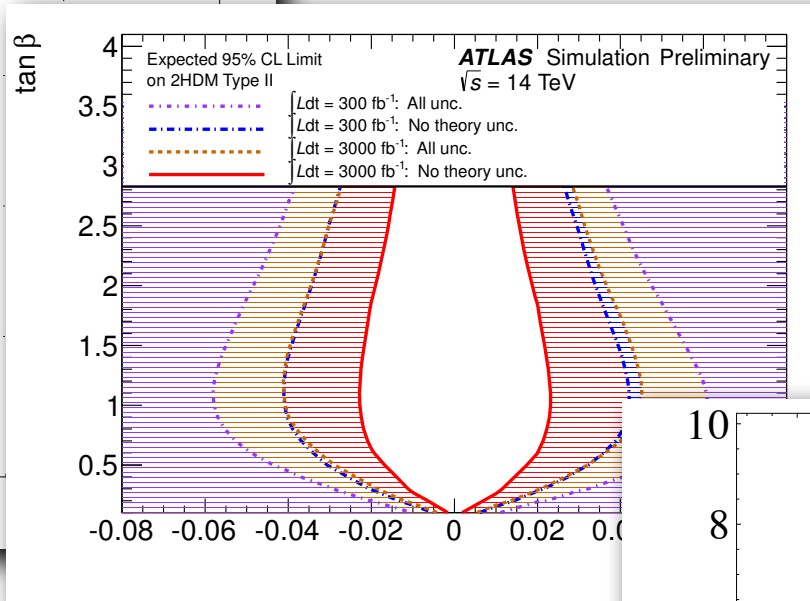
Dr. John Stupak (Purdue University Calumet)

LHC: H_{SM} implication on 2HDM

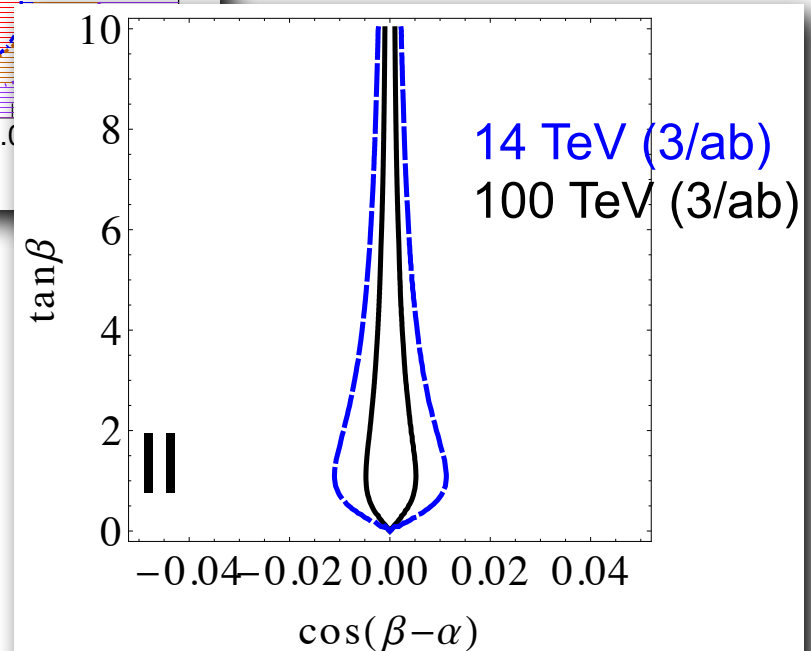
Type 2: Combined Fit [68, 95% CL]



ATLAS-PHYS-PUB-2013-015



Chen, SLAC workshop



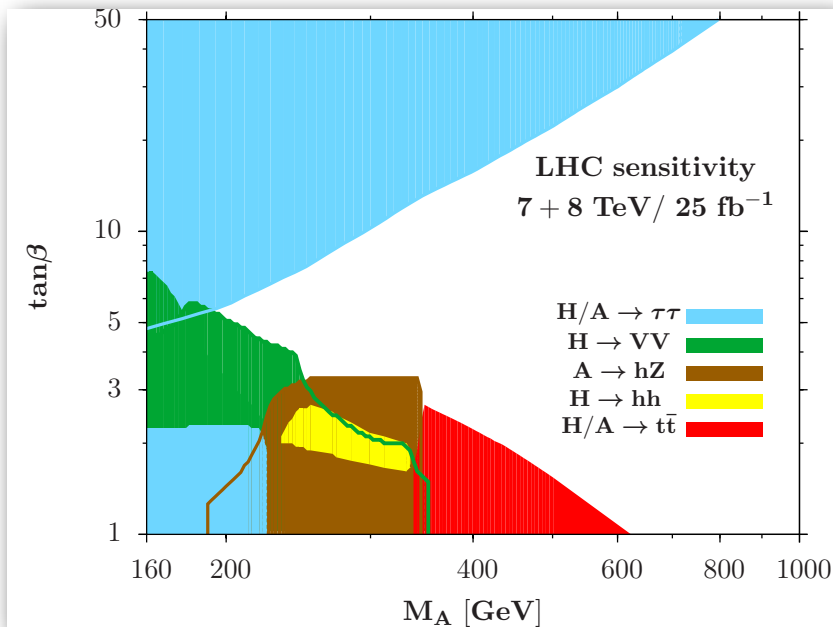
Craig, Galloway, Thomas, 1305.2424

Extended Higgs sector (other Higgs)
 Dr. John Stupak (Purdue University Calumet)

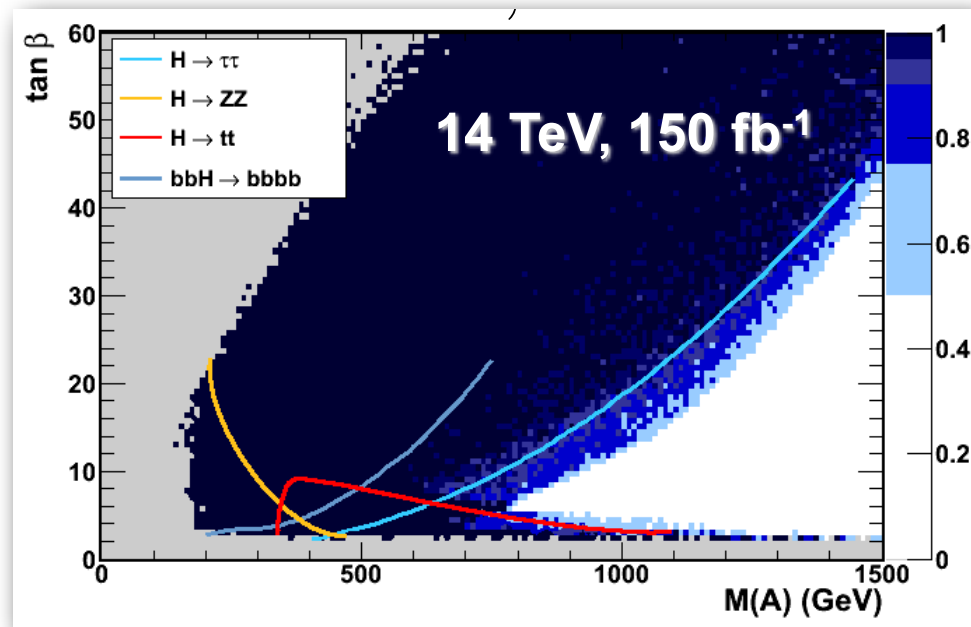
S. Su

LHC: MSSM

Higgs related SUSY and BSM phenomena
Prof. Carlos Wagner (U.of Chicago and ANL)



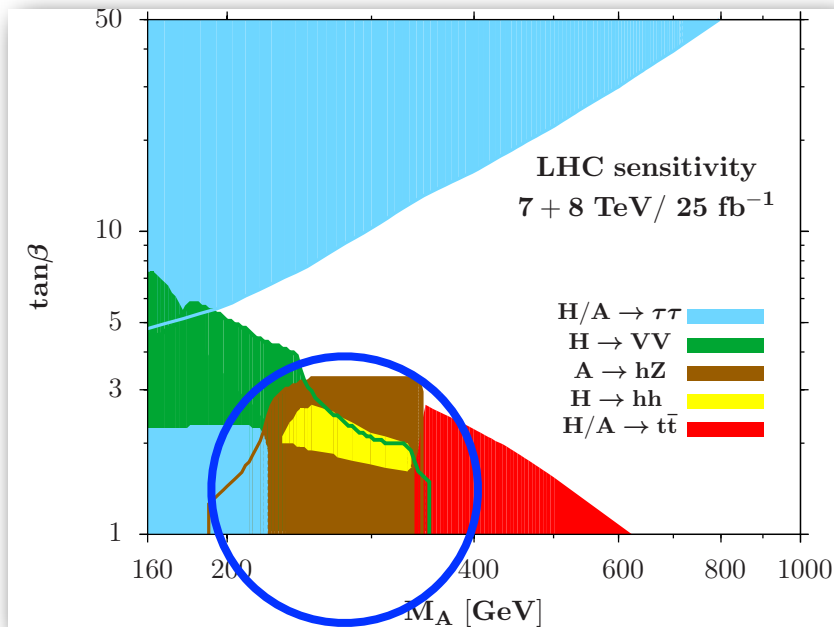
Snowmass 2013, Higgs working group



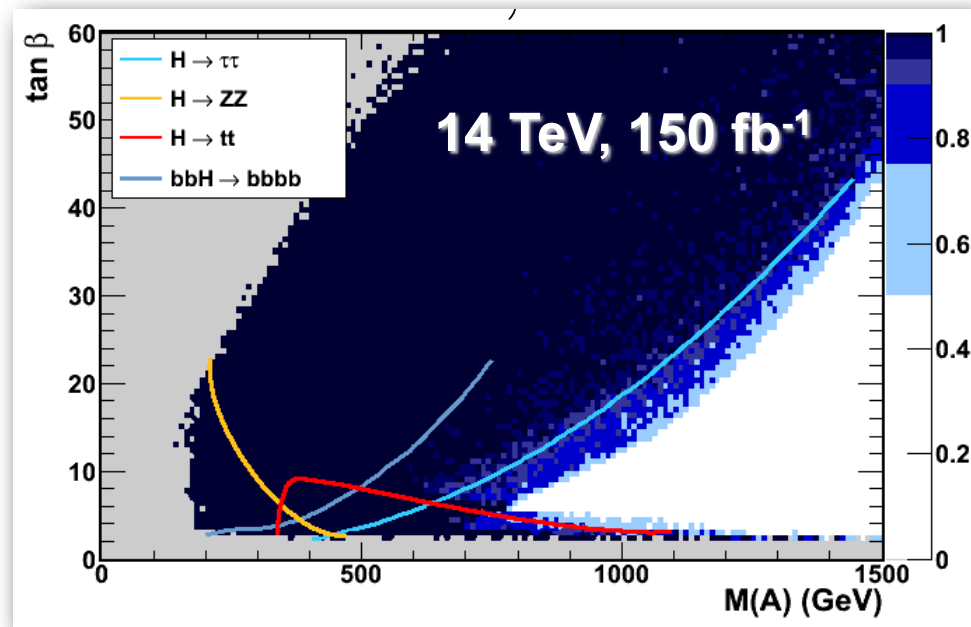
Arbey, Battaglia, Mahmoudi (2013)

LHC: MSSM

Higgs related SUSY and BSM phenomena
Prof. Carlos Wagner (U.of Chicago and ANL)



Snowmass 2013, Higgs working group

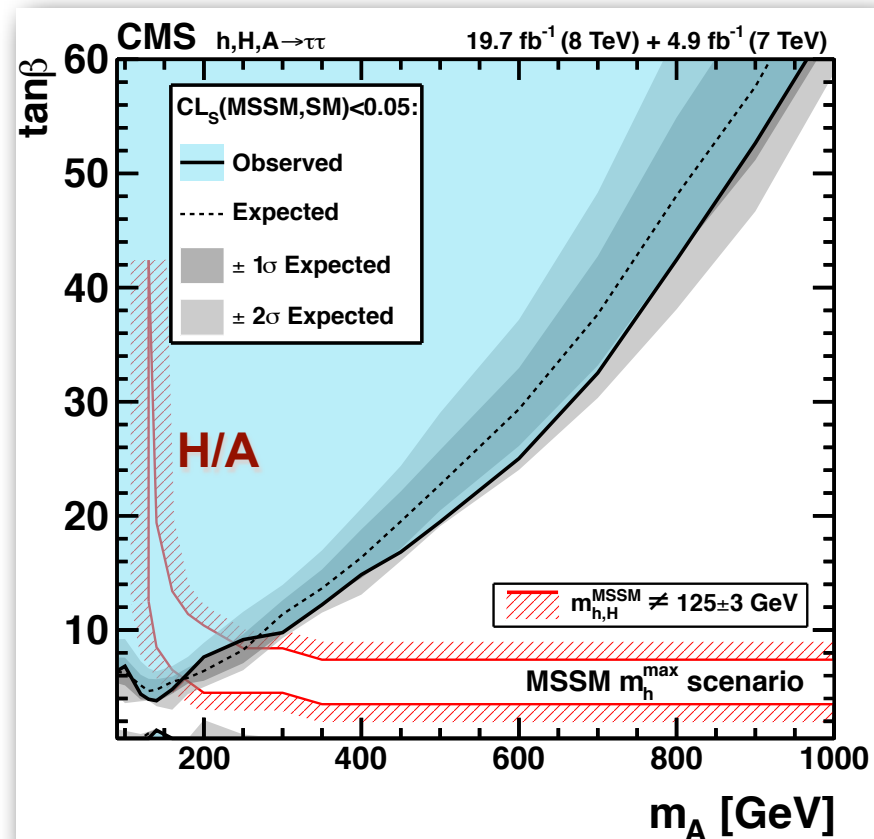
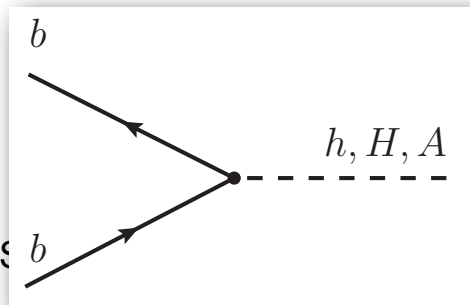
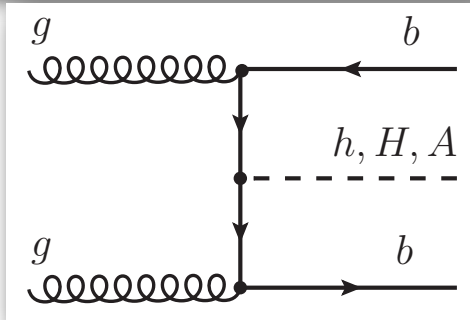
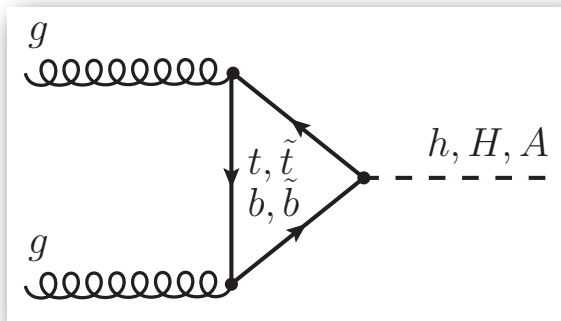


Arbey, Battaglia, Mahmoudi (2013)

LHC(now): BSM Higgses

SUSY and BSM Highlights from the LHC
James PILCHER (University of Chicago)

Conventional search channel: $H/A \rightarrow \gamma\gamma, ZZ, WW, \tau\tau, bb$
(even for non-SM Higgs)



Exotic Decay for Other Higgses

HH type	$(bb/\tau\tau/WW/ZZ)(bb/\tau\tau/WW/ZZ)$	$h_{SM} \rightarrow AA,$ $H \rightarrow h_{SM} h_{SM},$ $H \rightarrow AA,$ $A_i \rightarrow H_j A_k, \dots$
H^+H^- type	$(\tau\nu/tb)(\tau\nu/tb)$	$H/A \rightarrow H^+H^-$
ZH type	$(ll/qq/\nu\nu)(bb/\tau\tau/WW/ZZ)$	$h_{SM} \rightarrow ZA,$ $A \rightarrow Zh_{SM}, \dots$
WH^\pm type	$(lv/qq')(\tau\nu/tb)$	$H/A \rightarrow WH^\pm$
WH type	$(lv/qq')(bb/\tau\tau/WW/ZZ)$	tH^\pm production, $H^\pm \rightarrow WH$ $H^\pm \rightarrow WA$

Relax current limits

New channels open up for non-SM Higgs decay

Exotic Decay for Other Higgses

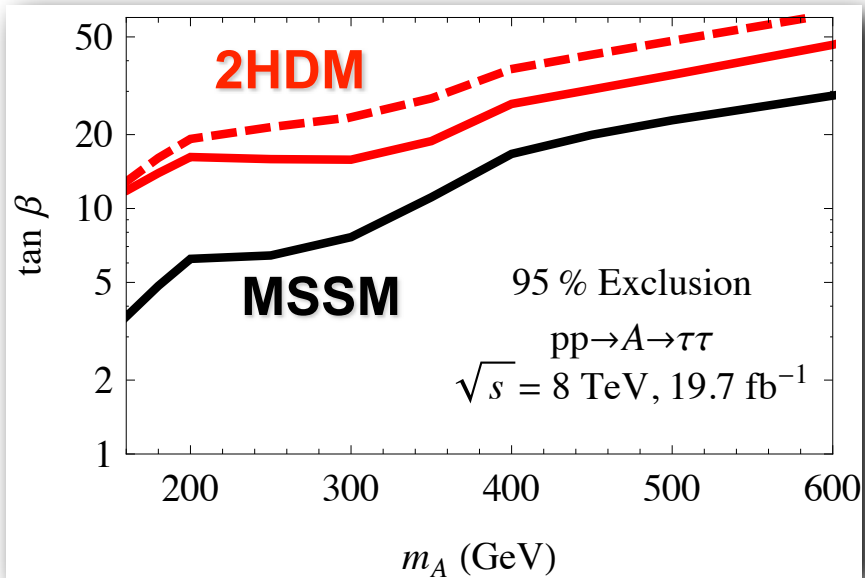
HH type	$(bb/\tau\tau/WW/ZZ)(bb/\tau\tau/WW/ZZ)$	$h_{SM} \rightarrow AA,$ $H \rightarrow h_{SM} h_{SM},$ $H \rightarrow AA,$ $A_i \rightarrow H_j A_k, \dots$
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WH^\pm type	$(lv/qq')(\tau\nu/tb)$	$H/A \rightarrow WH^\pm$
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Relax current limits

New channels open up for non-SM Higgs decay

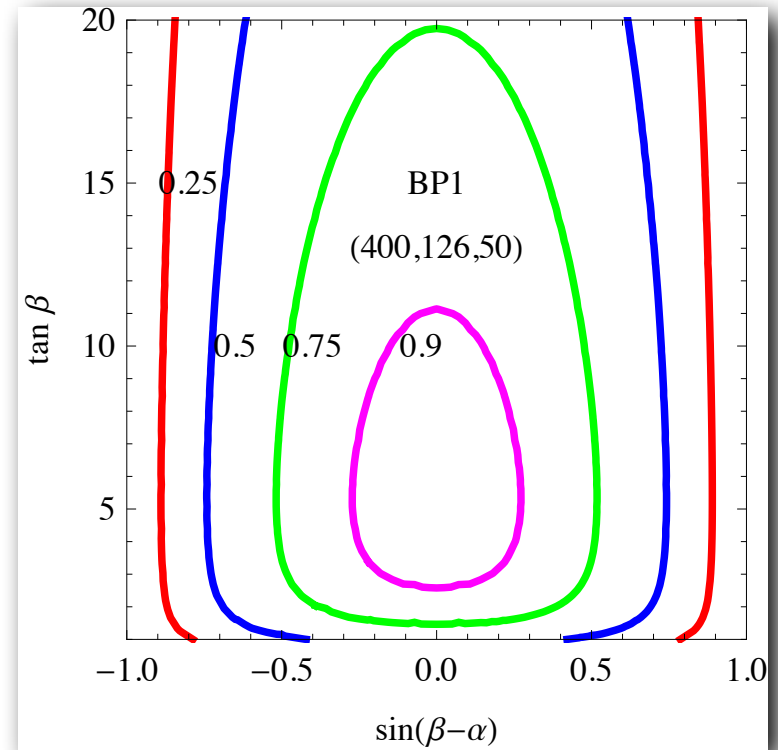
LHC: $H/A \rightarrow AZ/HZ$

$pp \rightarrow H/A \rightarrow \tau\tau$



B. Coleppa, F. Kling, SS (2014)

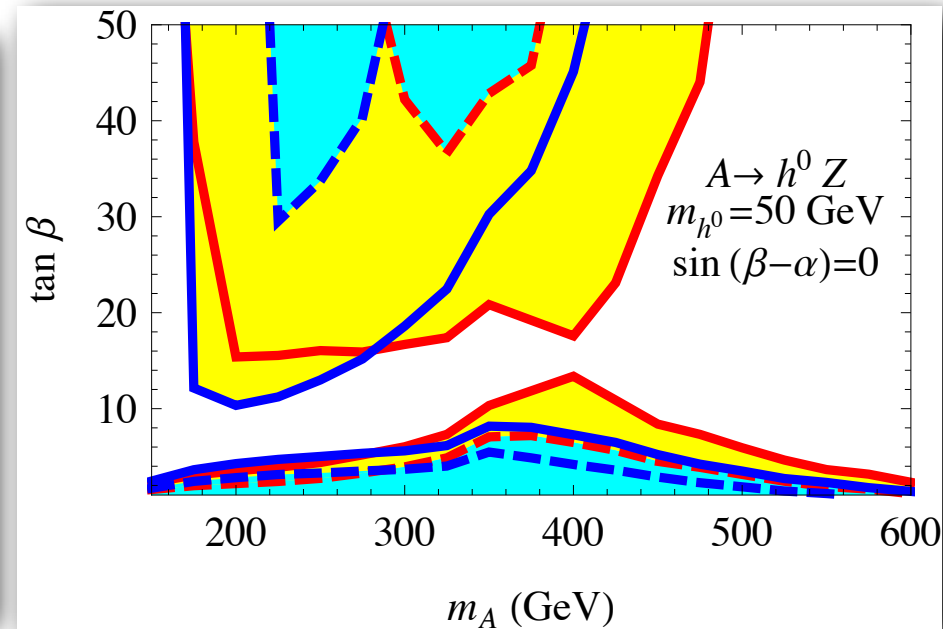
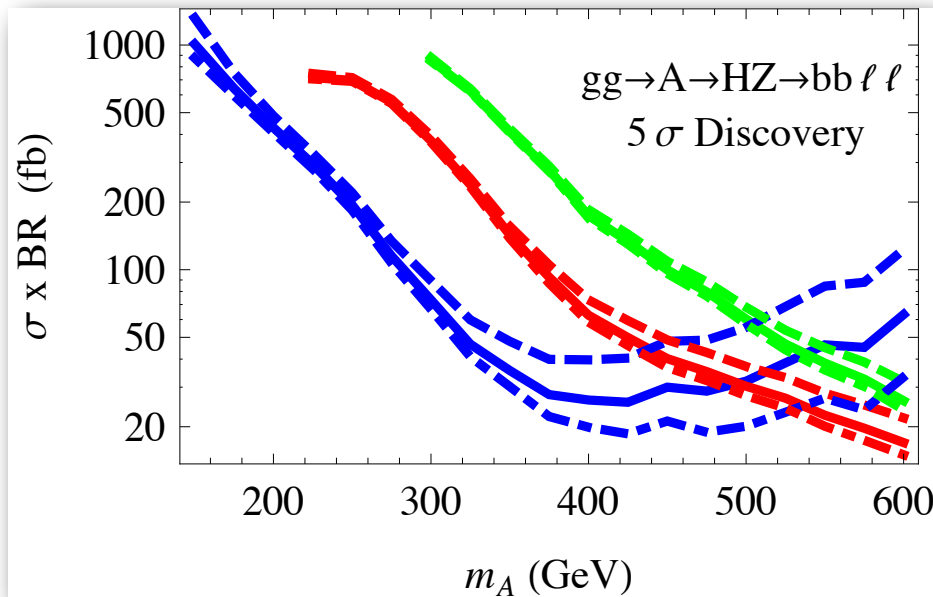
$pp \rightarrow H/A \rightarrow AZ/HZ \rightarrow \tau\tau \text{ II, } b\bar{b} \text{ II}$



LHC: $H/A \rightarrow AZ/HZ$

$pp \rightarrow H/A \rightarrow AZ/HZ \rightarrow \tau\tau \ell\ell, b\bar{b}\ell\ell$

LHC 14, 100 fb⁻¹

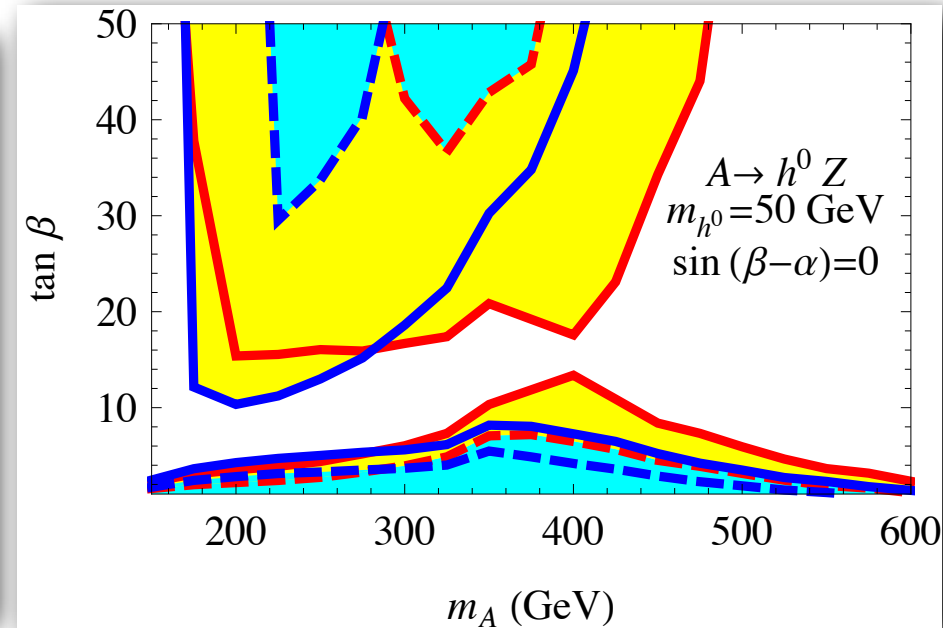
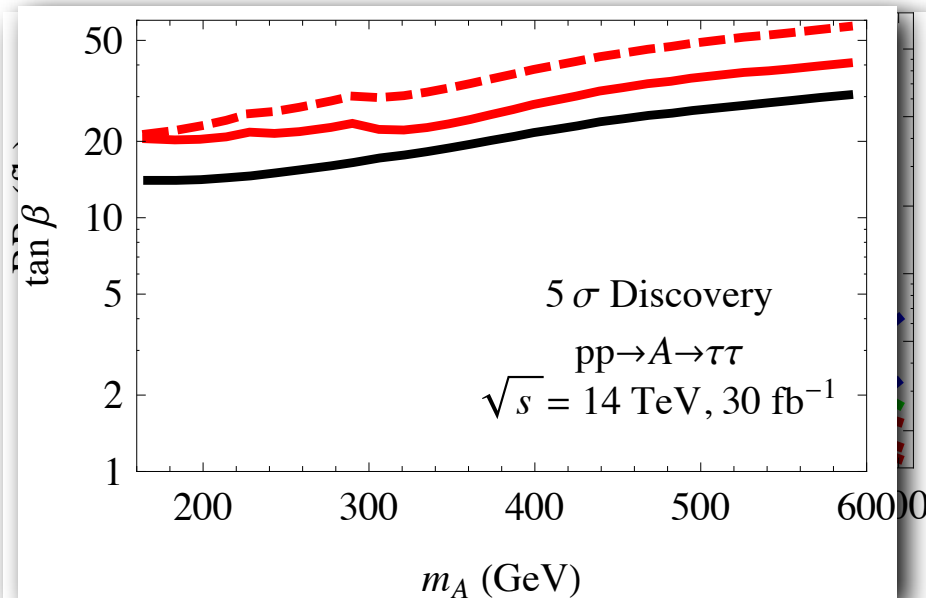


B. Coleppa, F. Kling, SS (2014)

LHC: $H/A \rightarrow AZ/HZ$

$pp \rightarrow H/A \rightarrow AZ/HZ \rightarrow \tau\tau \text{ ll}, b\text{ll}$

LHC 14, 100 fb⁻¹

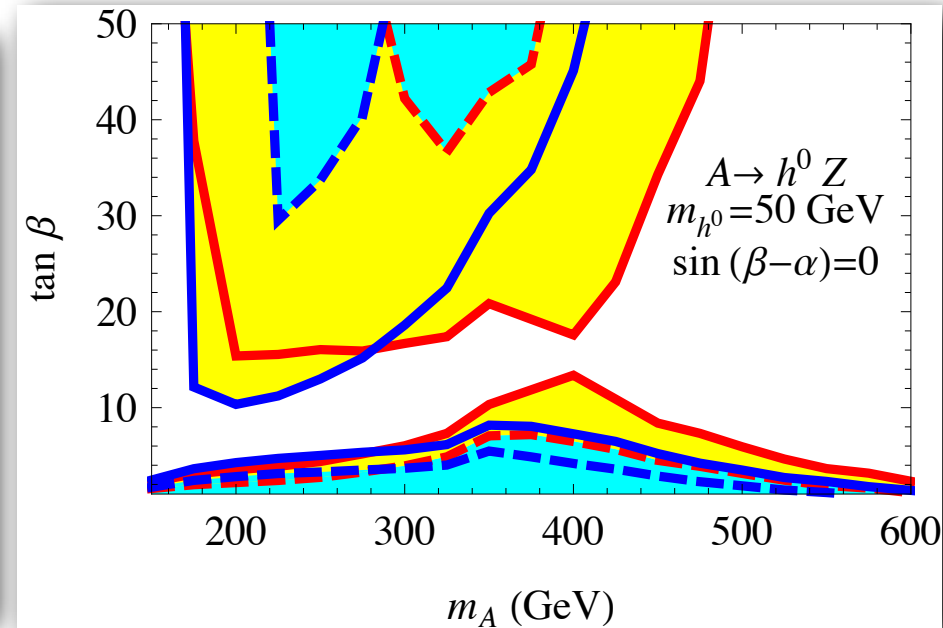
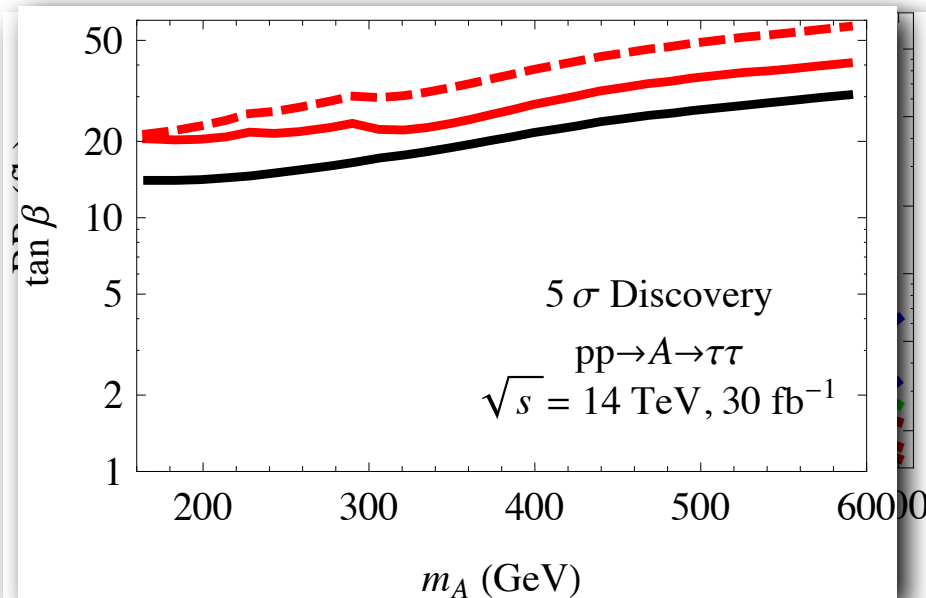


B. Coleppa, F. Kling, SS (2014)

LHC: $H/A \rightarrow AZ/HZ$

$pp \rightarrow H/A \rightarrow AZ/HZ \rightarrow \tau\tau, ll, b\bar{b}$

LHC 14, 100 fb⁻¹

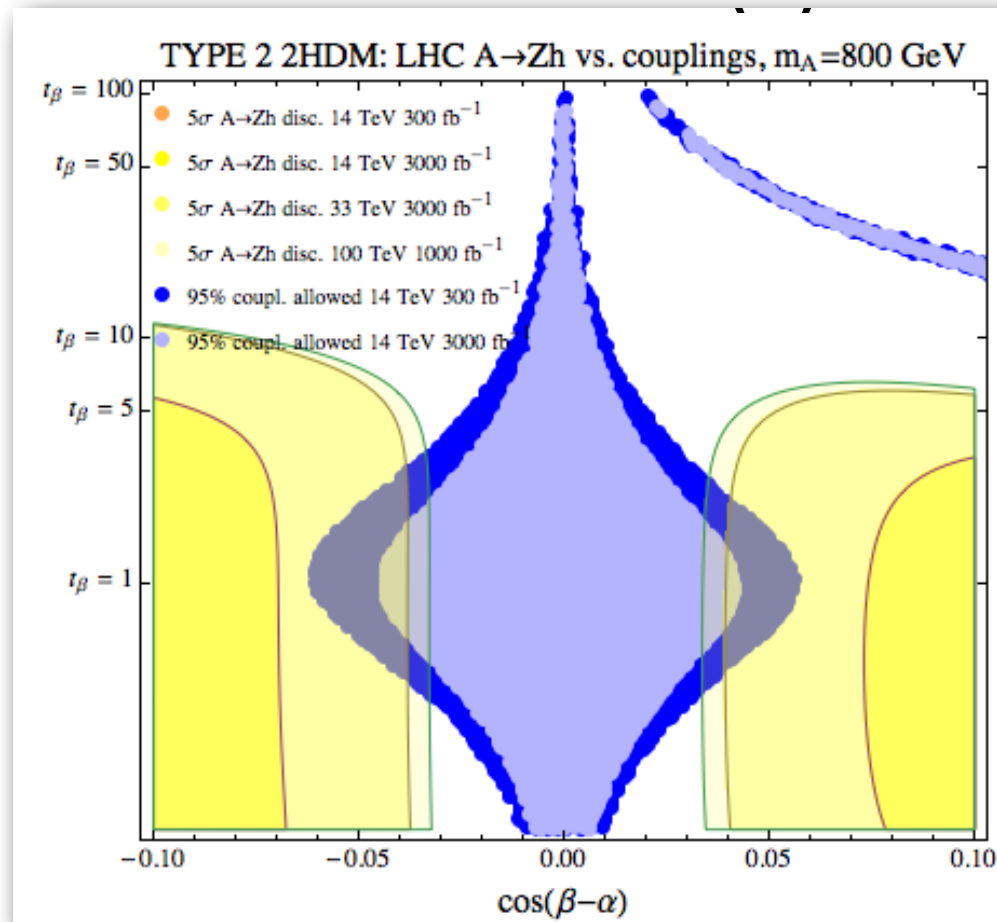


B. Coleppa, F. Kling, SS (2014)

complementary to the conventional $\tau\tau$ mode

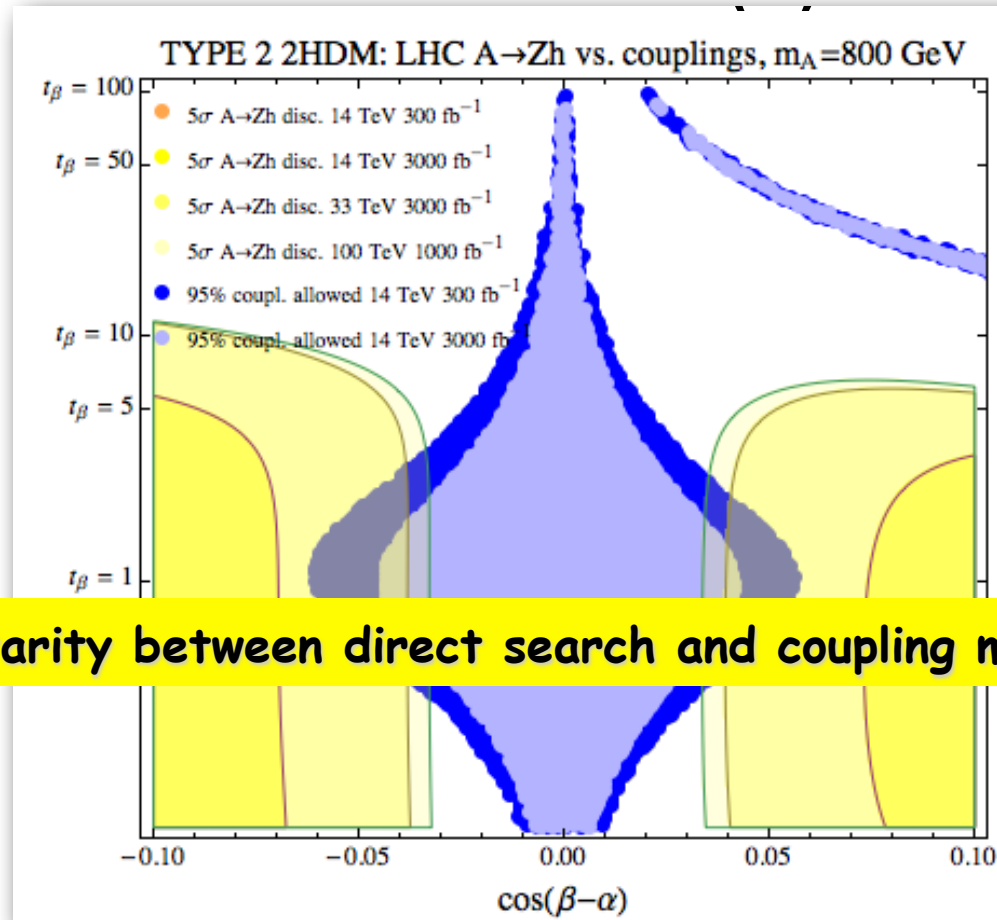
$pp \rightarrow H/A \rightarrow AZ/HZ \rightarrow \tau\tau \text{ II, } b\bar{b} \text{ II}$

Brownson et. al., 1308.6334



$pp \rightarrow H/A \rightarrow AZ/HZ \rightarrow \tau\tau, ll, b\bar{b}$

Brownson et. al., 1308.6334

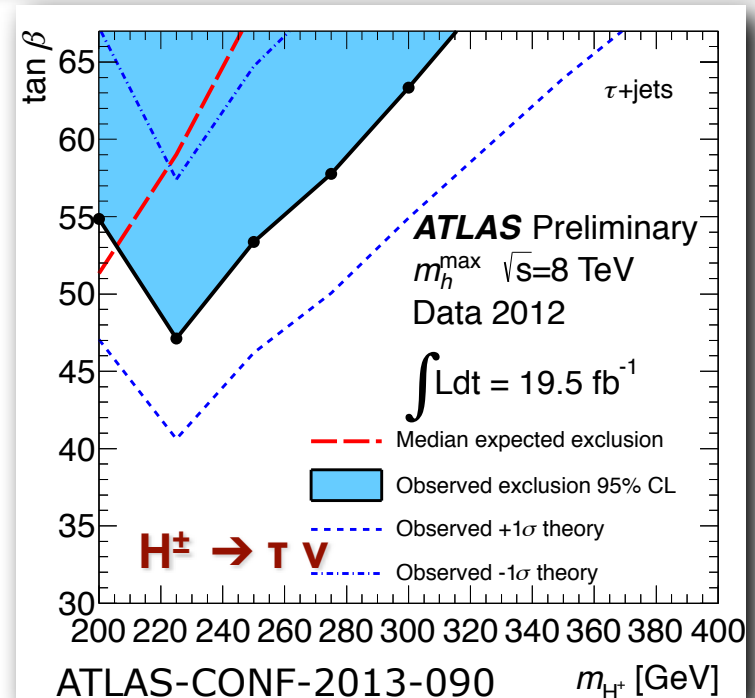
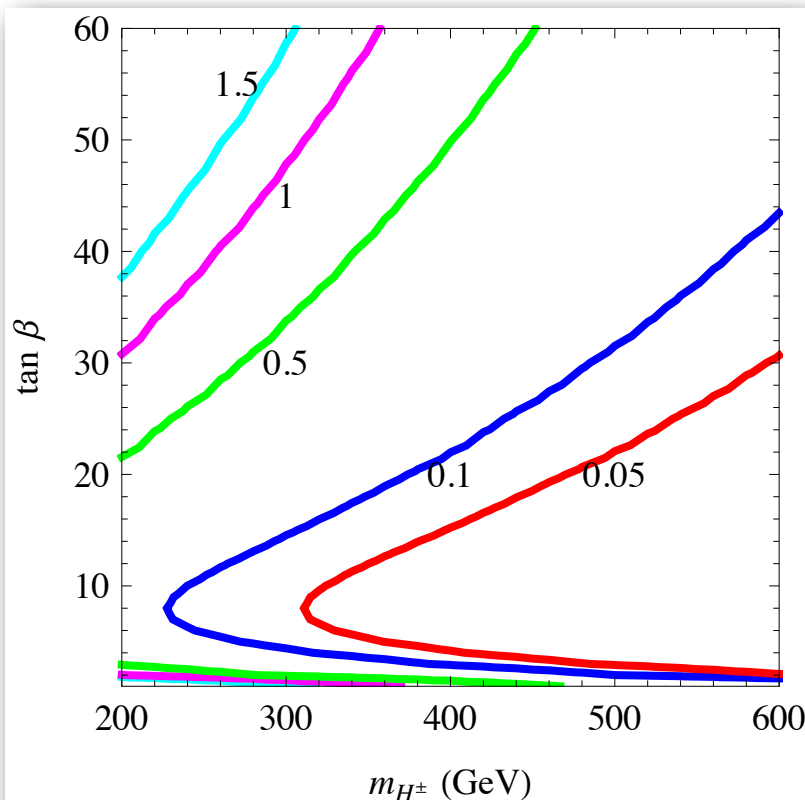
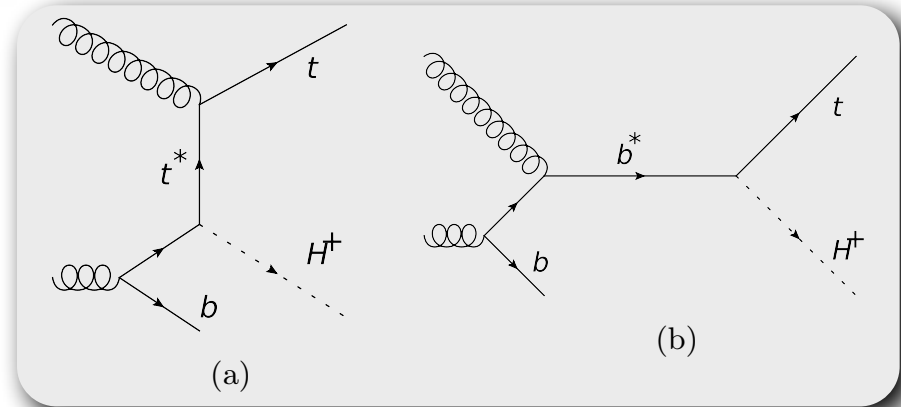


complementarity between direct search and coupling measurements.

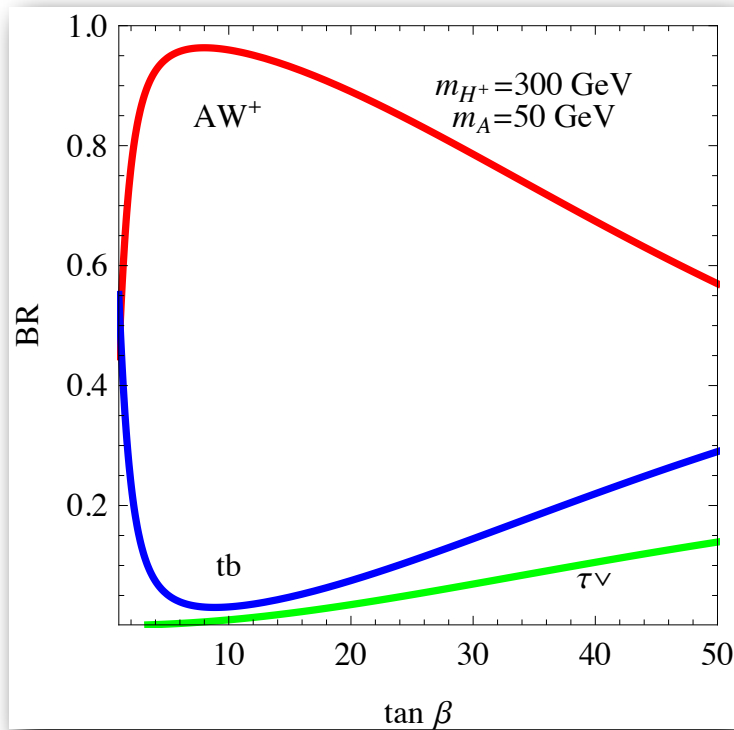
LHC: $H^\pm \rightarrow AW/HW$

Charged Higgs search is difficult!

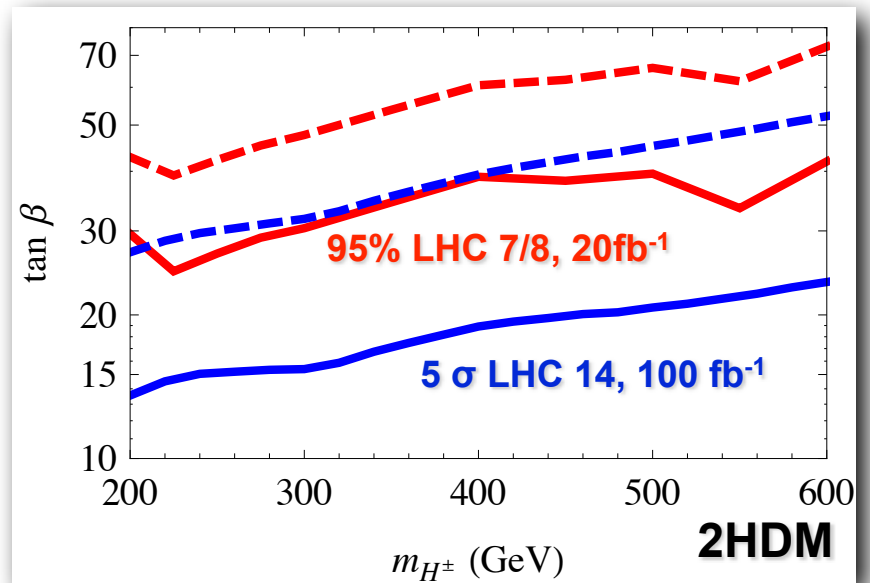
- small production cross section
- $H^\pm \rightarrow tb$, large backgrounds
- $H^\pm \rightarrow \tau\nu$, cs, suppressed signal



LHC: H^\pm



$pp \rightarrow H^\pm tb \rightarrow \tau\nu bbjj$

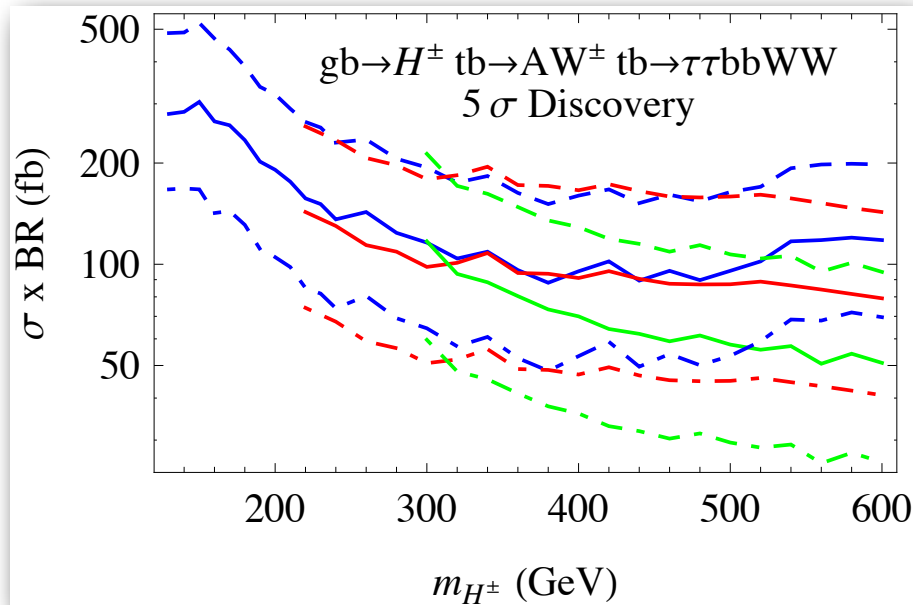


B. Coleppa, F. Kling, SS (2014)

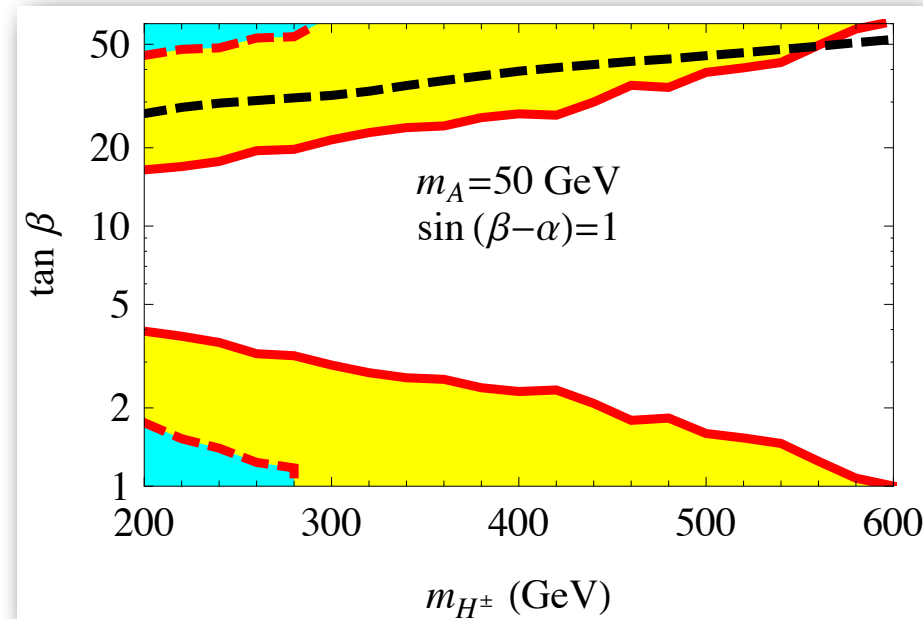
LHC: H^\pm

$pp \rightarrow H^\pm \text{ } tb \rightarrow AW/HW \text{ } tb \rightarrow \tau\tau \text{ } bb \text{ } lv \text{ } qq$

LHC 14, 300 fb^{-1}



B. Coleppa, F. Kling, SS (2014)

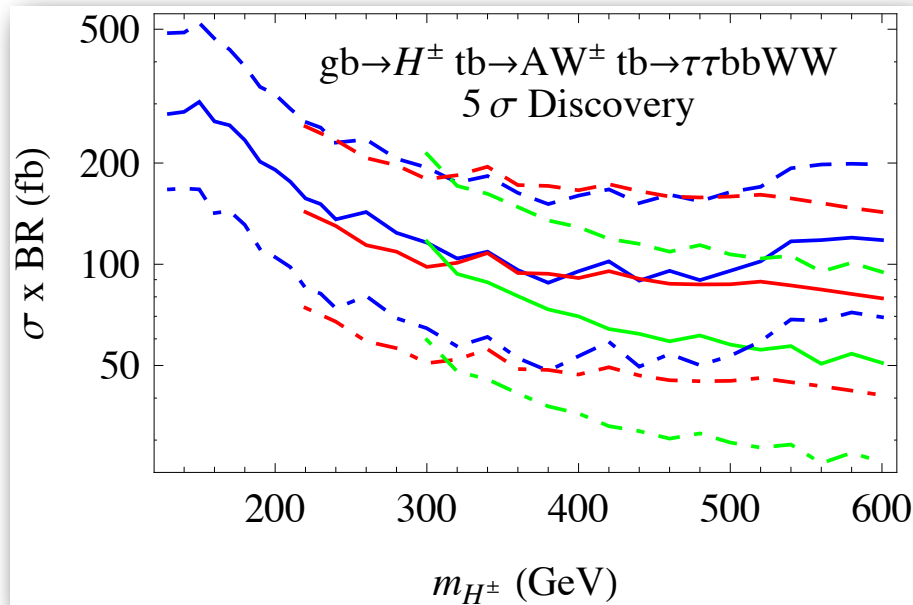


Type II 2HDM

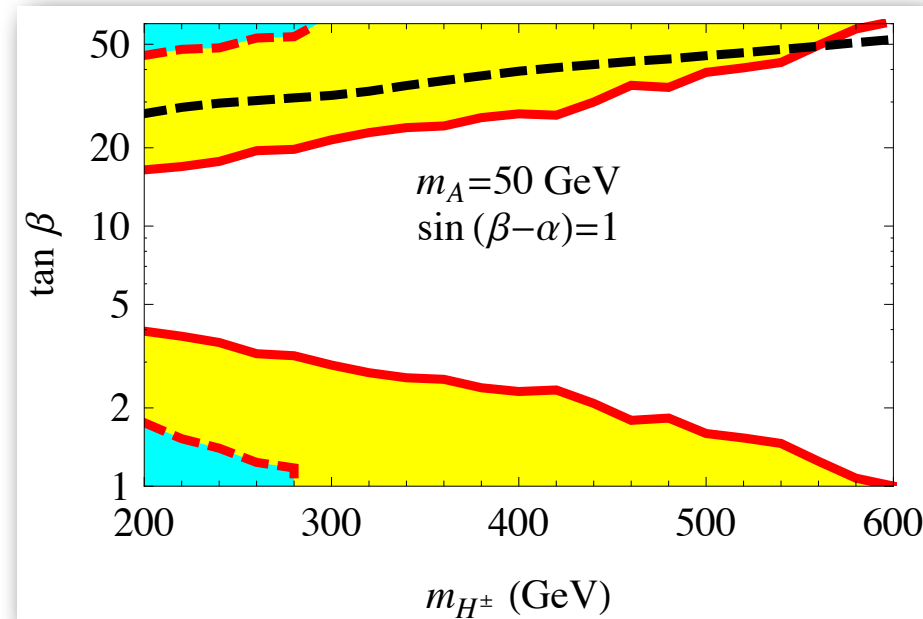
LHC: H^\pm

$pp \rightarrow H^\pm \text{ } tb \rightarrow AW/HW \text{ } tb \rightarrow \tau\tau \text{ } bb \text{ } lv \text{ } qq$

LHC 14, 300 fb^{-1}



B. Coleppa, F. Kling, SS (2014)



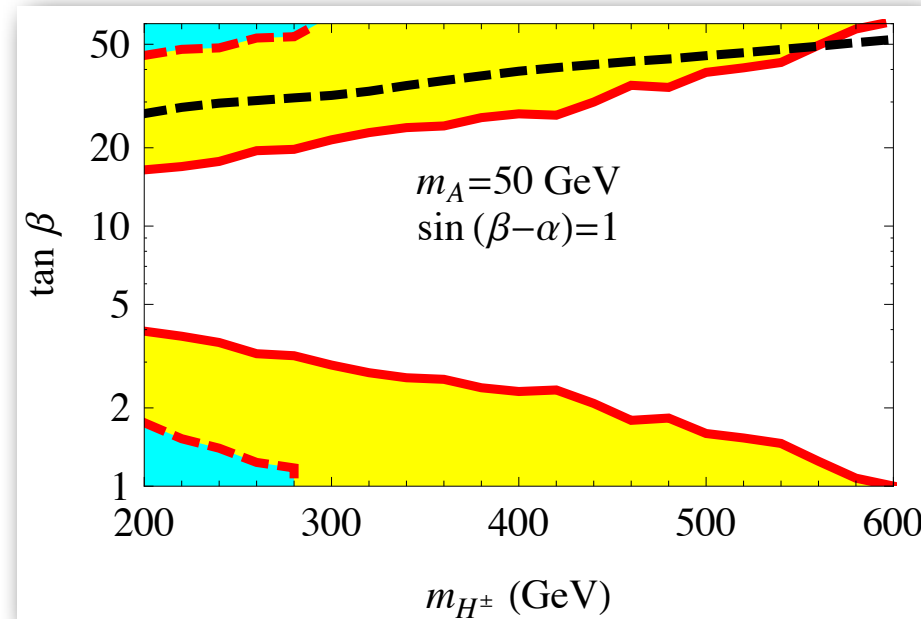
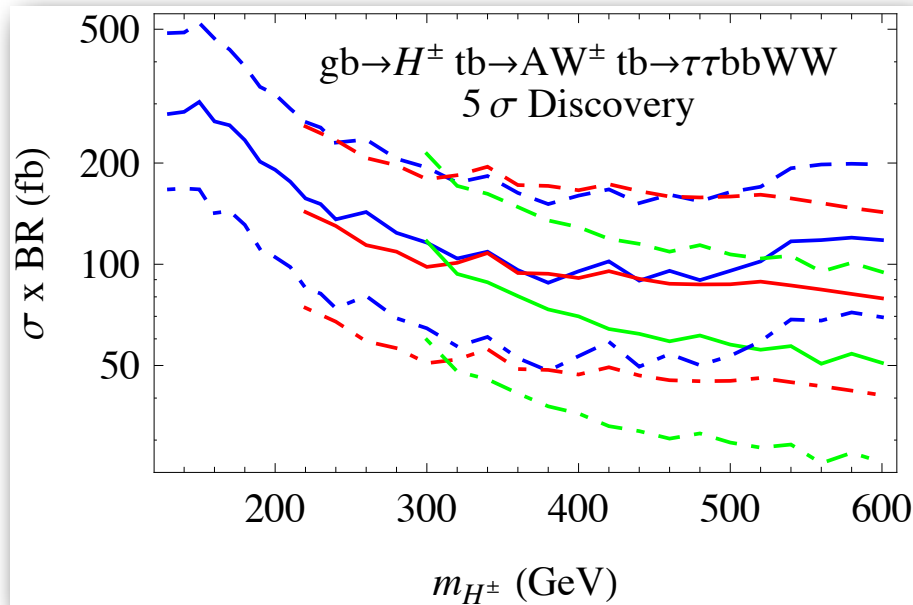
Type II 2HDM

Reach at small $\tan \beta$: complementary to the $H^\pm \rightarrow \tau\nu$ channel

LHC: H^\pm

$pp \rightarrow H^\pm \text{ } tb \rightarrow AW/HW \text{ } tb \rightarrow \tau\tau \text{ } bb \text{ } lv \text{ } qq$

LHC 14, 300 fb^{-1}



B. Coleppa, F. Kling, SS (2014)

Type II 2HDM

Reach at small $\tan \beta$: complementary to the $H^\pm \rightarrow \tau\nu$ channel

100 TeV reach for BSM Higgses needed,

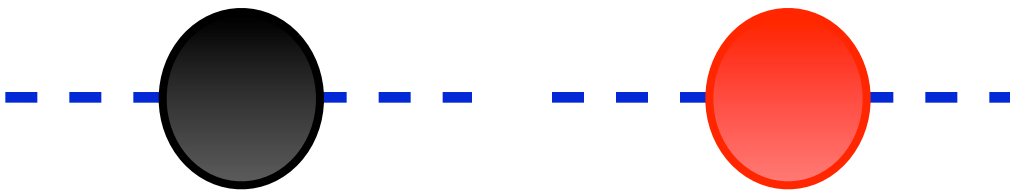
both for conventional channels and exotic channels.

S. Su

Naturalness and Top Partners

$$\epsilon \sim (125 \text{ GeV}/M_{\text{NP}})^2$$

Naturalness: Top Partner


$$(m_H^2)_{\text{physical}} \sim (m_H^2)_{\text{bare}} + \Lambda_{\text{cutoff}}^2 - \Lambda_{\text{cutoff}}^2$$

- ⊙ A light Higgs mass and top contribution \Rightarrow top partner @ TeV scale
- ⊙ top partner \rightarrow top (or bW) + X

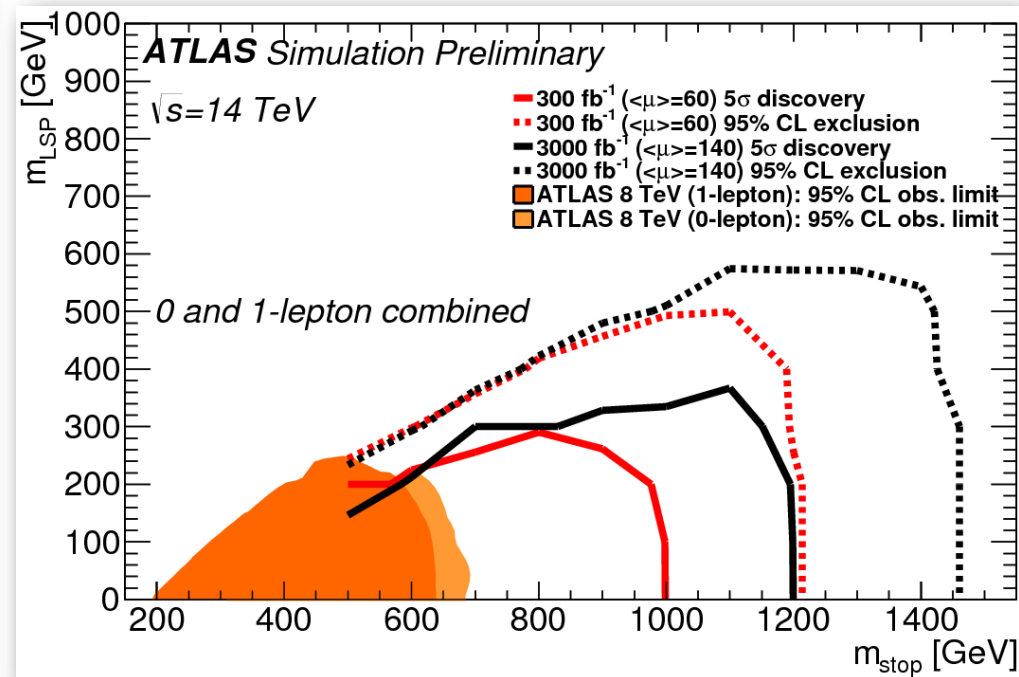
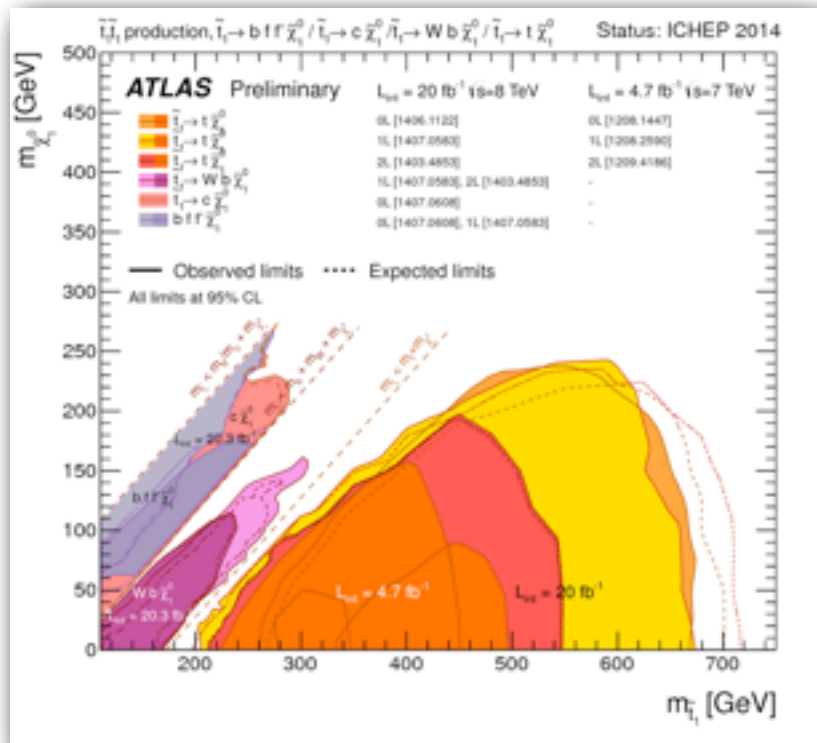
Top partners including SUSY stop productions, Aram Avetisyan (Boston University)
Composite Higgs, Giuliano Panico (CERN & ETH Zurich)

decay might be highly suppressed.

- ⊙ top partner not necessarily charged under $SU(3)_c$
could hide at the LHC or pp machine (strong production)

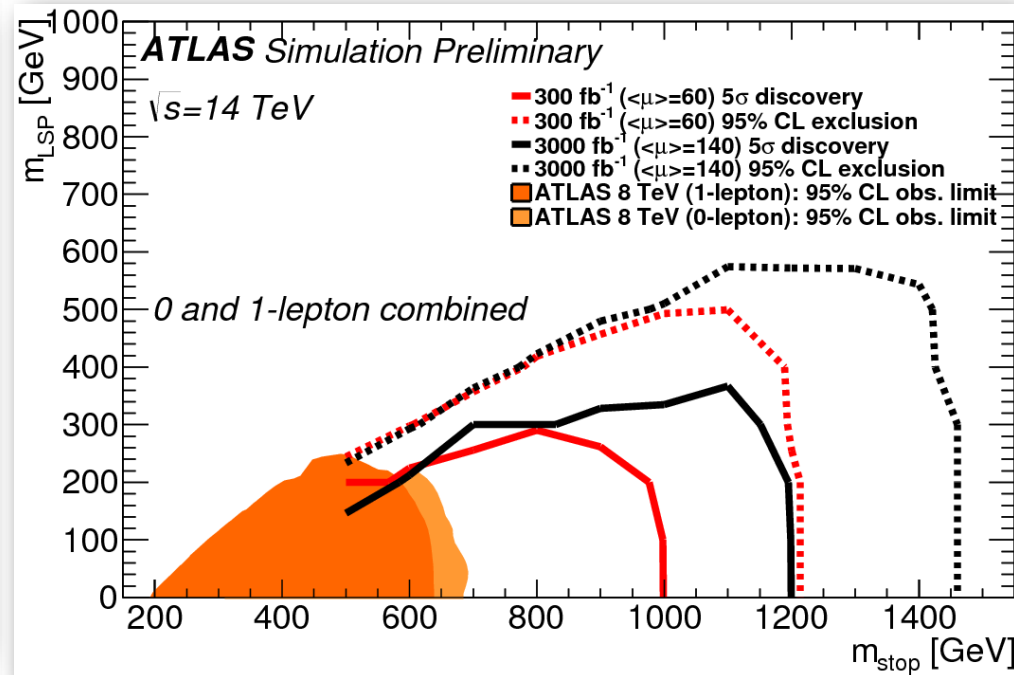
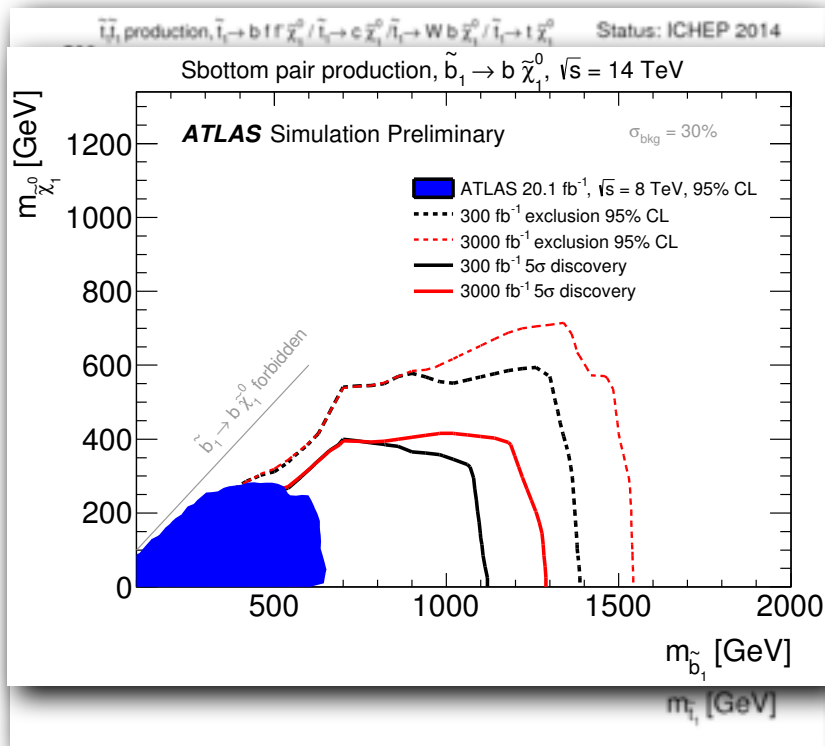
LHC/HL-LHC: stop

Prospects of New Physics searches using HL-LHC Altan Cakir (DESY)



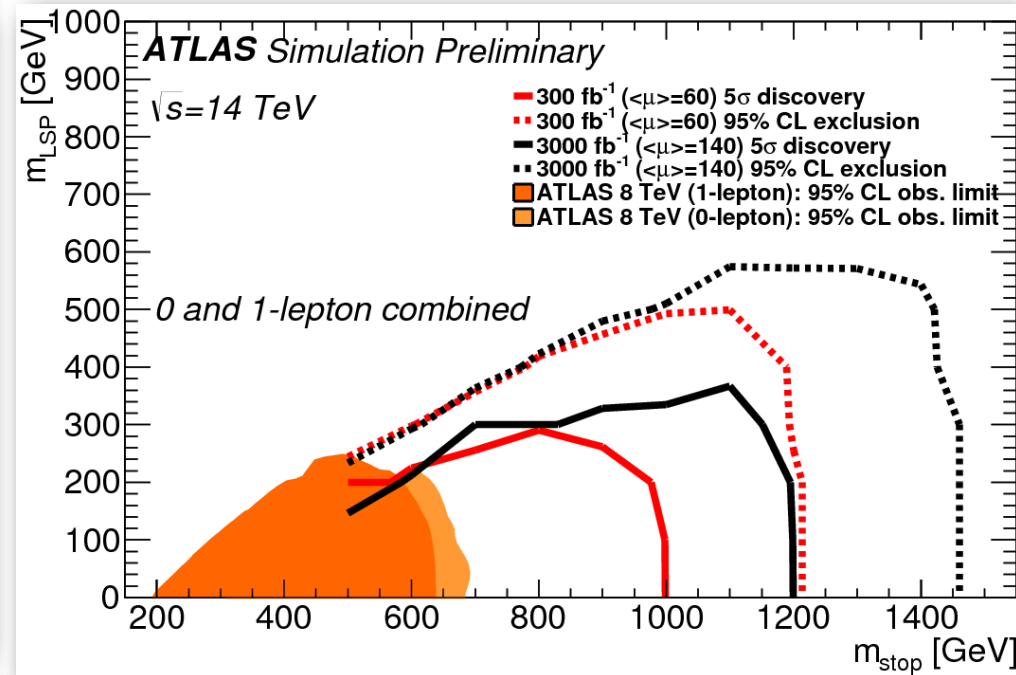
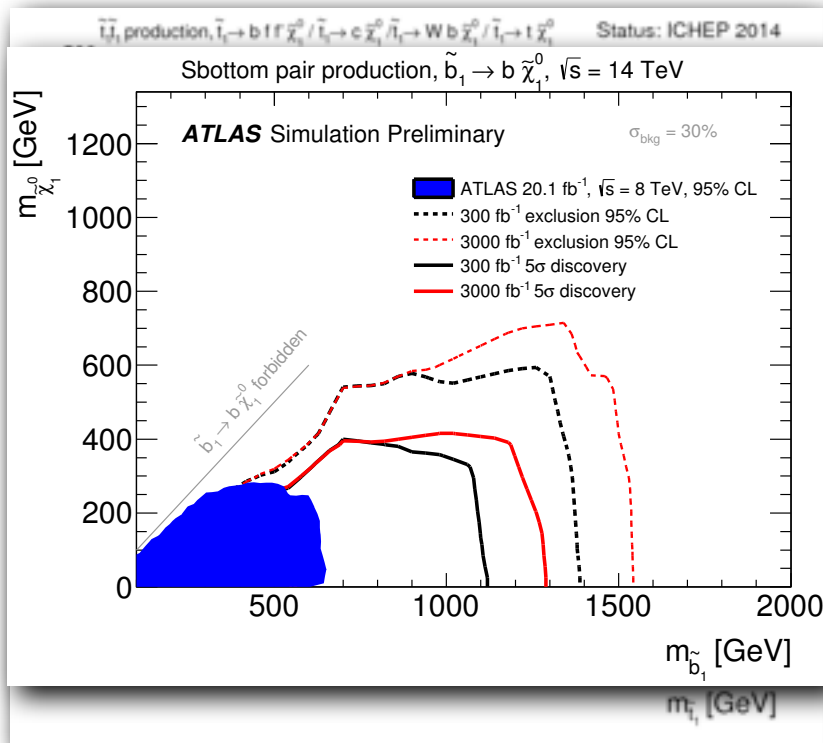
LHC/HL-LHC: stop

Prospects of New Physics searches using HL-LHC Altan Cakir (DESY)



LHC/HL-LHC: stop

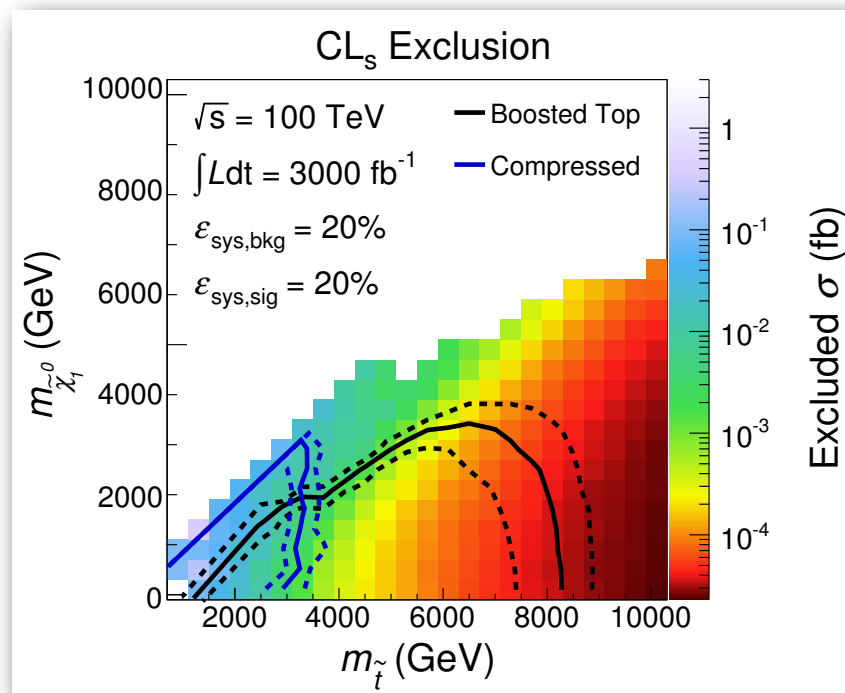
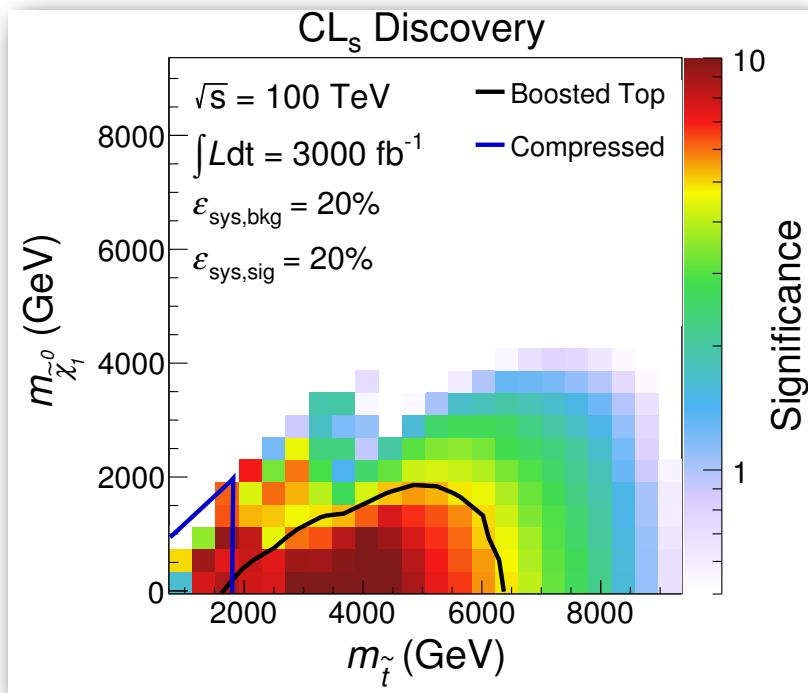
Prospects of New Physics searches using HL-LHC
Altan Cakir (DESY)



- Mass reach extended by a factor of 2 at 14 TeV, 300 fb⁻¹
- further extended by 20% at 3 ab⁻¹
- If no excess seen at 300 fb⁻¹, can not be seen at 3 ab⁻¹

100 TeV pp: Stop

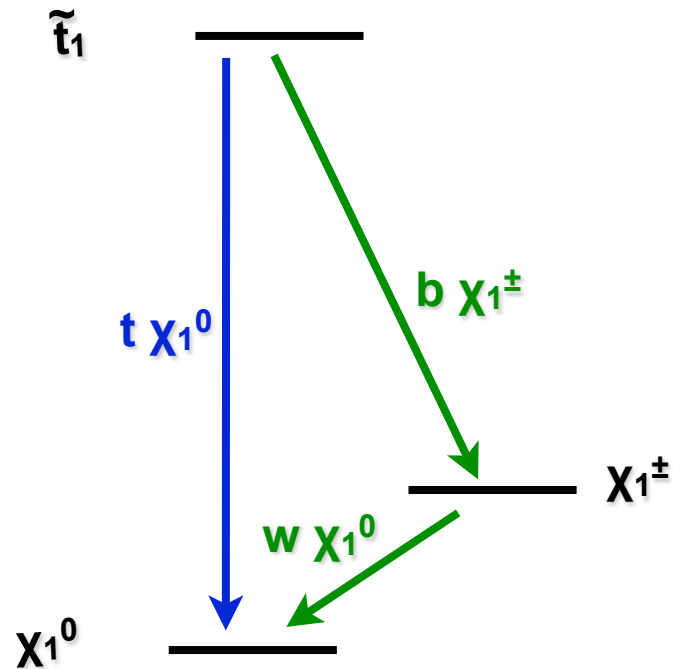
SUSY Colored production with gluinos and squarks
Mike Hance (LBNL)



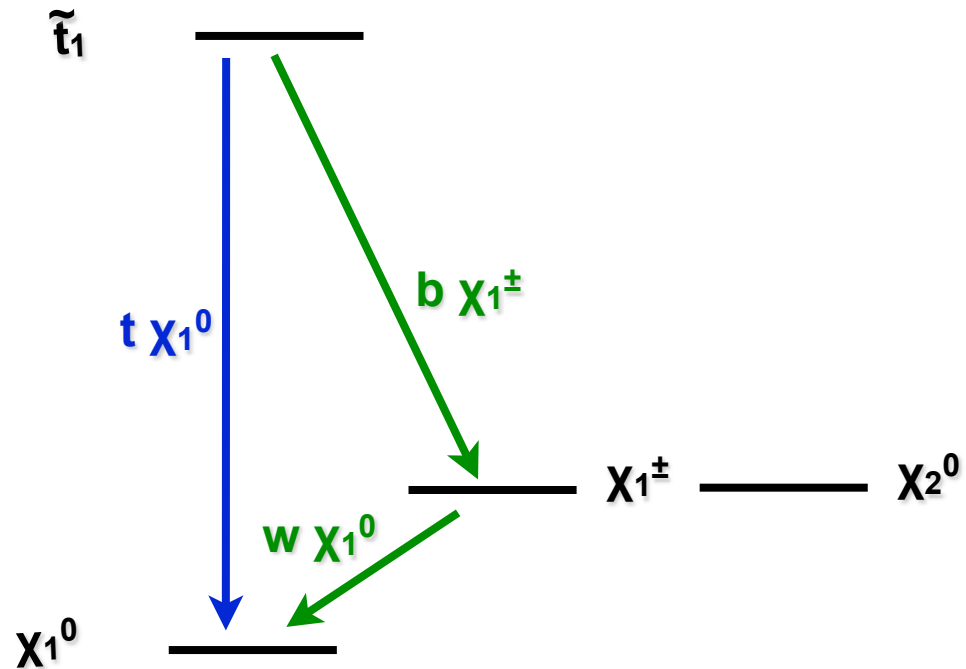
T. Cohen et. al, 1406.4512

- HL-LHC: mass, coupling, decay channels, spin
- 100 TeV pp: stop-stop-h production
- ILC: light stop $< E_{\text{cm}}/2$

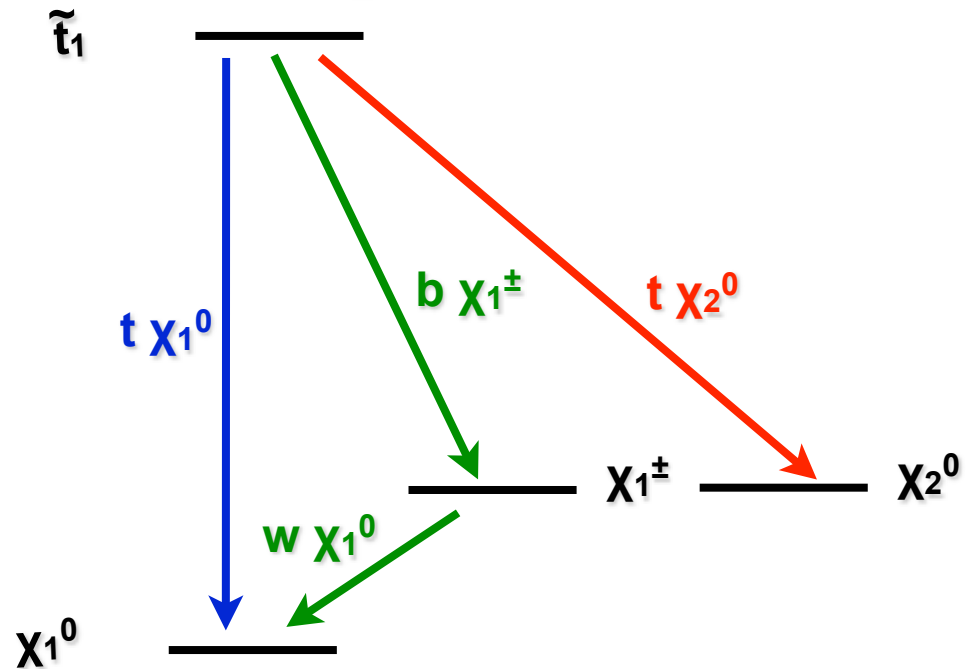
Stop decay



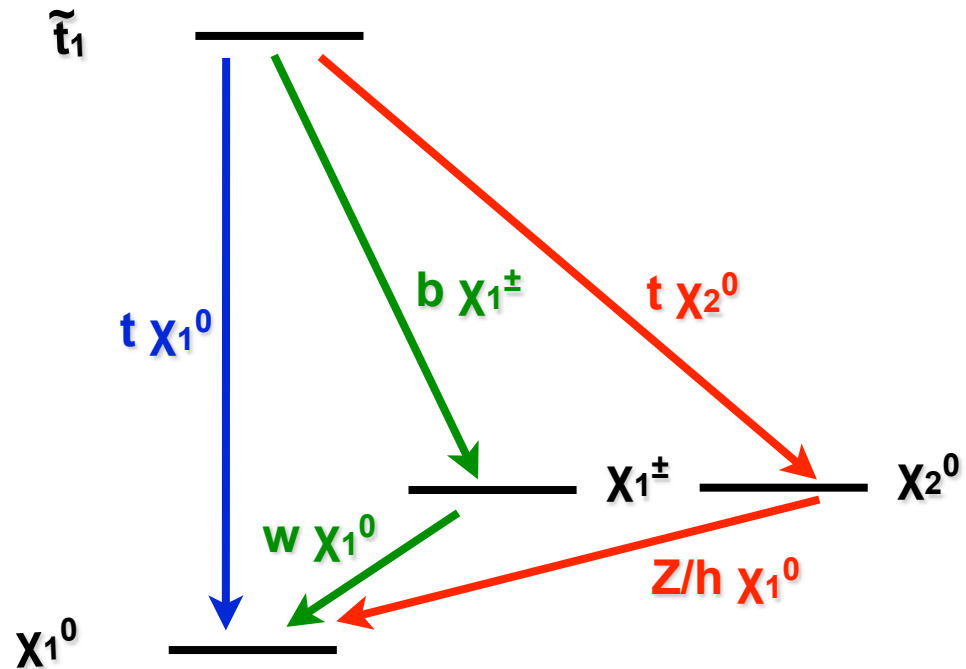
Stop decay



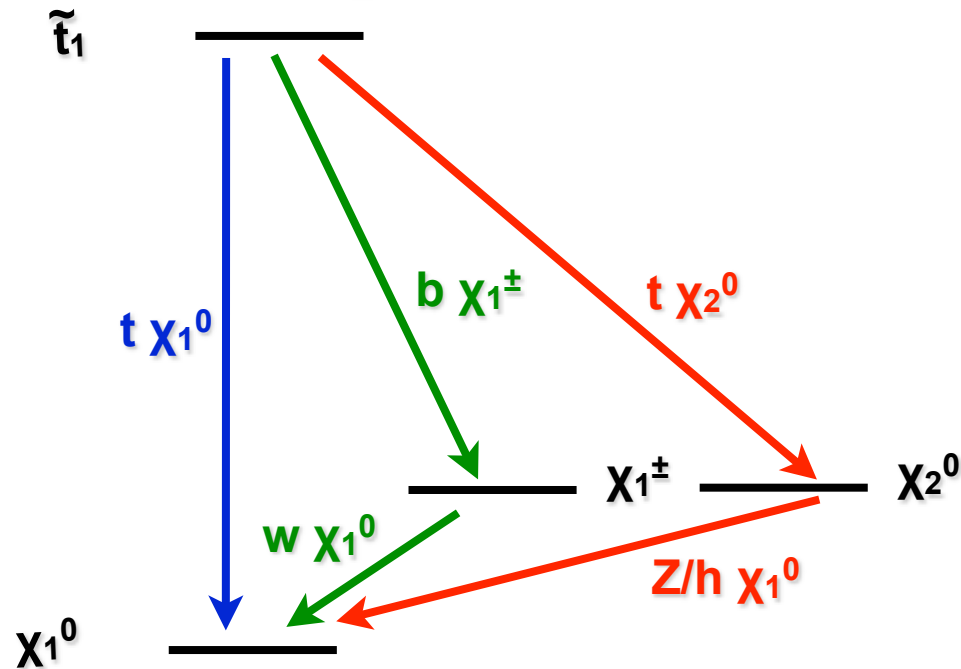
Stop decay



Stop decay



Stop decay

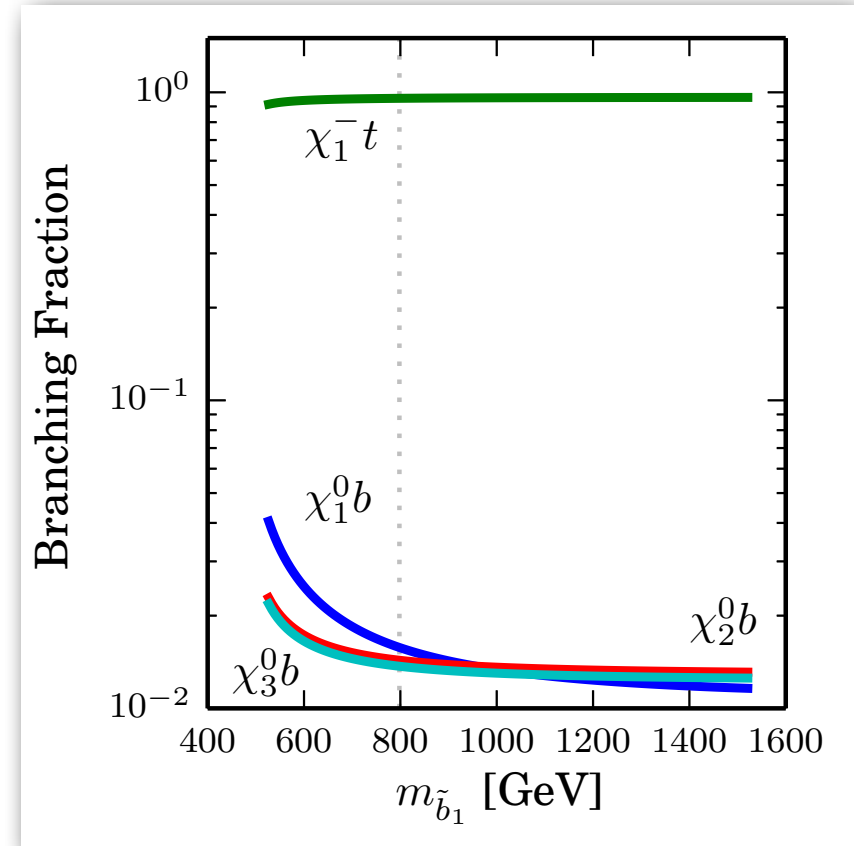
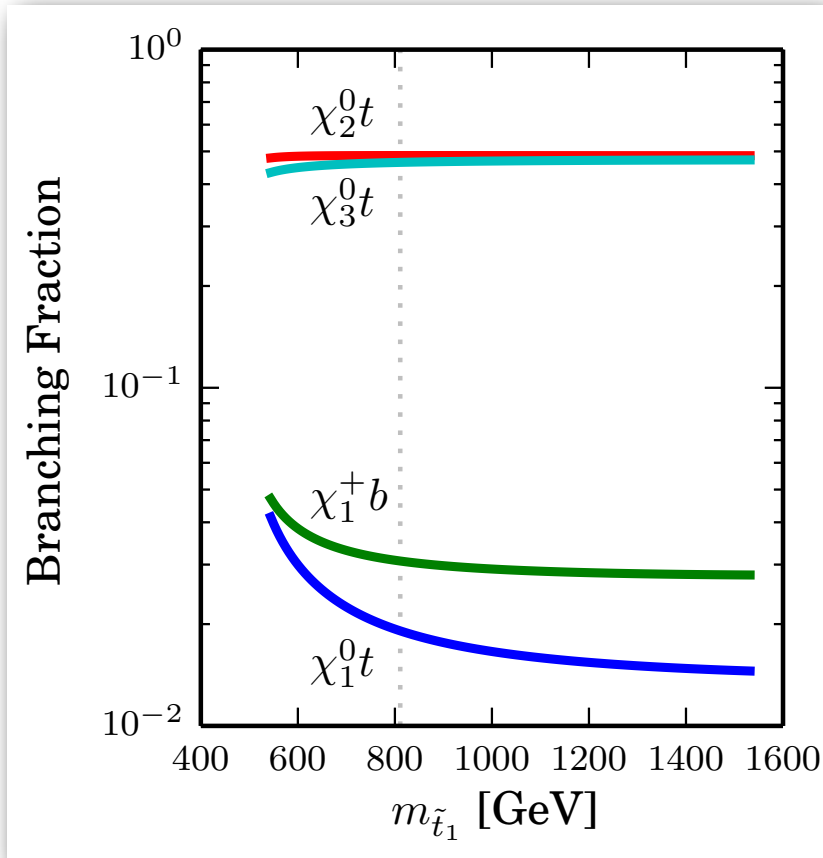


$t \chi_{2^0}$ could be competitive

- Current limit based on $t \chi_{1^0}$ and $b \chi_{1^\pm}$ become much weaker
- new final state for stop searches:
(bW)(tZ/h)MET, (tZ/h)(tZ/h)MET

Stop decay

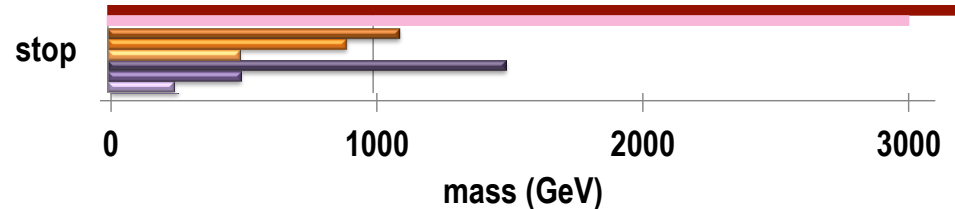
J. Eckel, SS, H. Zhang (2014)



Higgsino NLSP, Bino LSP, left stop/sbottom

Naturalness

$$\epsilon \sim (125 \text{ GeV}/M_{\text{NP}})^2$$



- LHC: TeV scale for top partner, $\epsilon \sim 1\%$
- HL-LHC:
 - increase the reach by 10-20%, measure top partner property
- 100 TeV VLHC: 10 TeV level, $\epsilon \sim 10^{-4}$
- ILC: $E_{\text{cm}}/2$, 1 TeV machine, $\epsilon \sim 1\%$

Precision measurements, multi TeV level

SUSY and BSM Physics opportunities with higher energy proton colliders

Raman Sundrum (University of Maryland)

Dark Matter

$$m_{\text{WIMP}} \leq 2 \text{ TeV} \left(\frac{g_{\text{eff}}^2}{0.3} \right)$$

Dark Matter, WIMPS or Axions

Prof. Liantao Wang (University of Chicago)

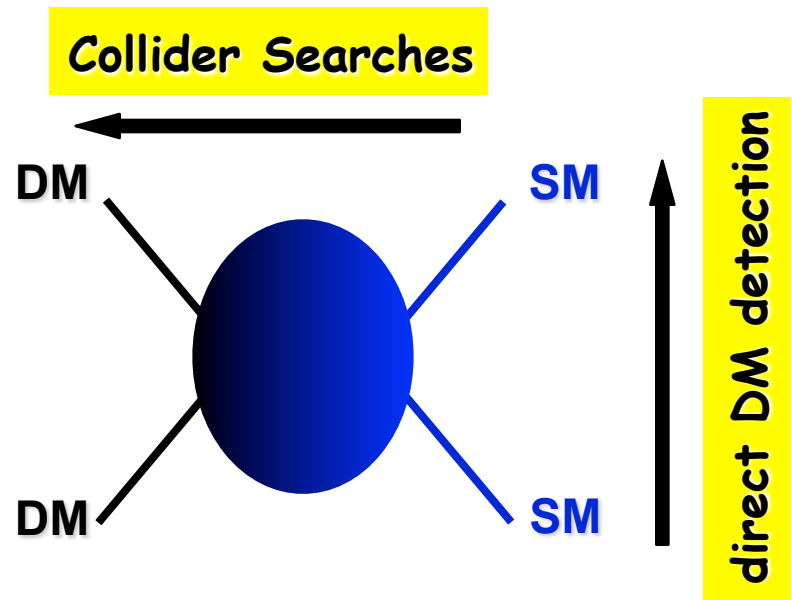
Vector boson productions associated with new physics

Prof. Bhaskar Dutta (Texas A&M University)

Effective operator

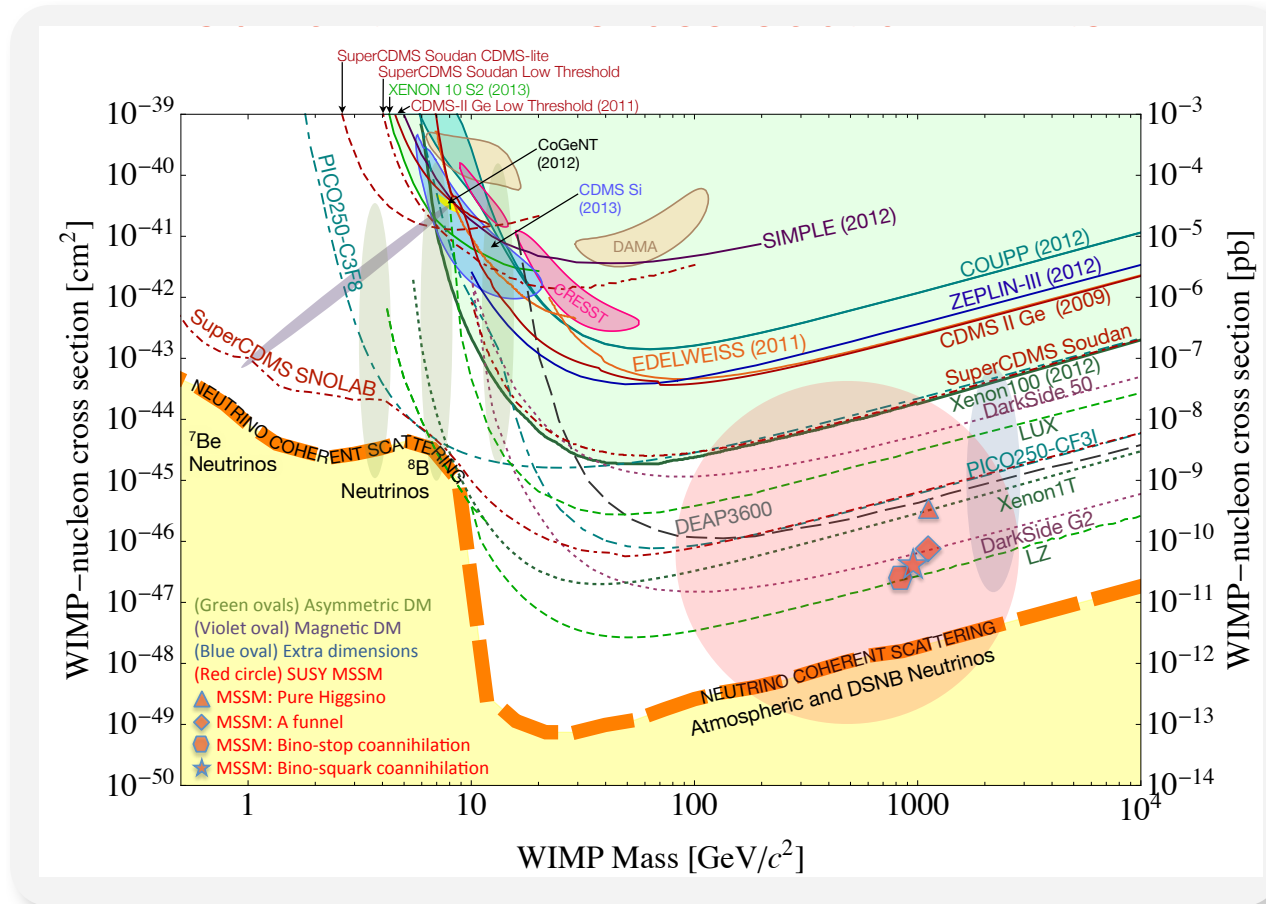
- study effective operators that couples DM to SM quarks/gluons
- same operator also contribute to DM direct detection: **complementary**

$$m_{\text{WIMP}} \leq 2 \text{ TeV} \left(\frac{g_{\text{eff}}^2}{0.3} \right)$$



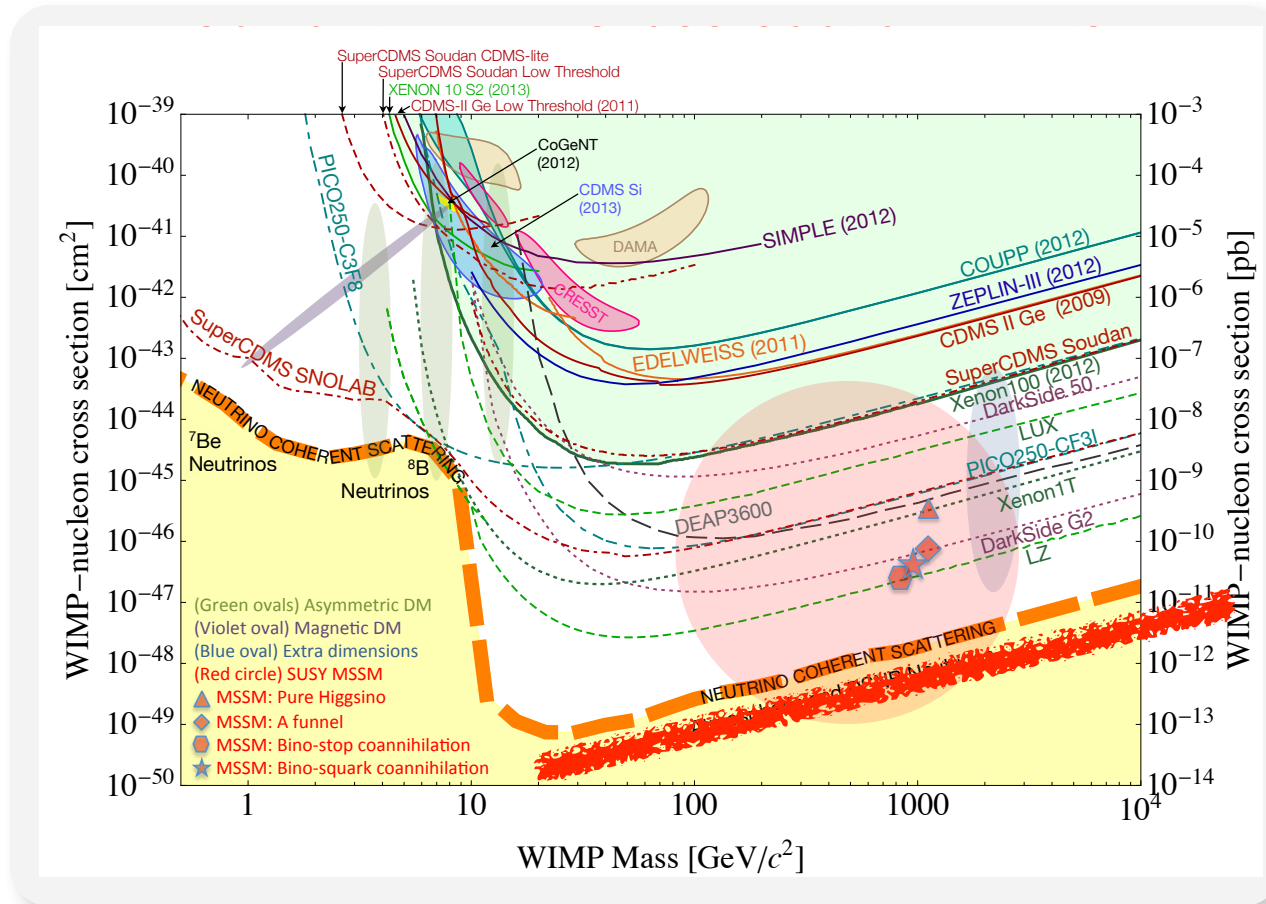
Direct detection versus collider reach

LUX collaboration, 2013



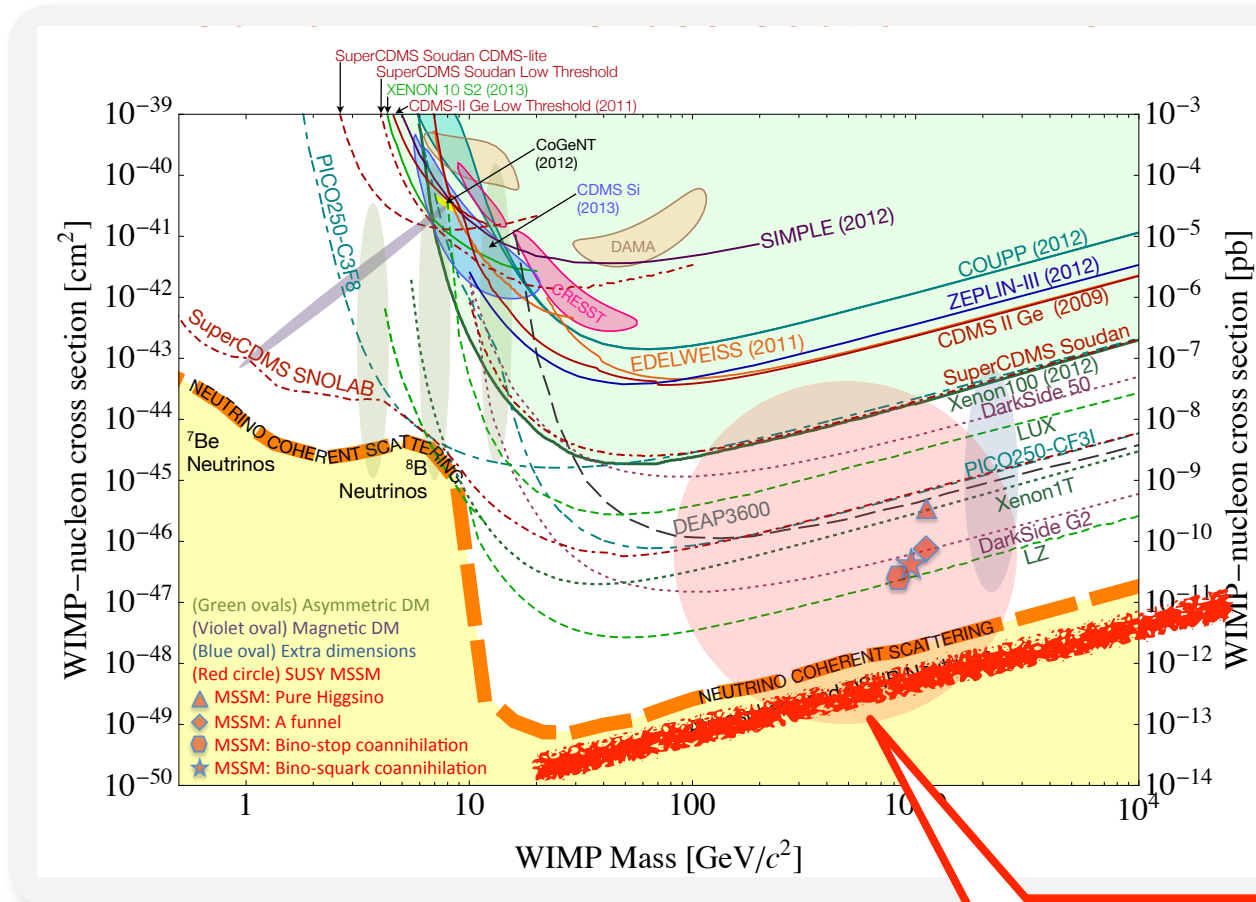
Direct detection versus collider reach

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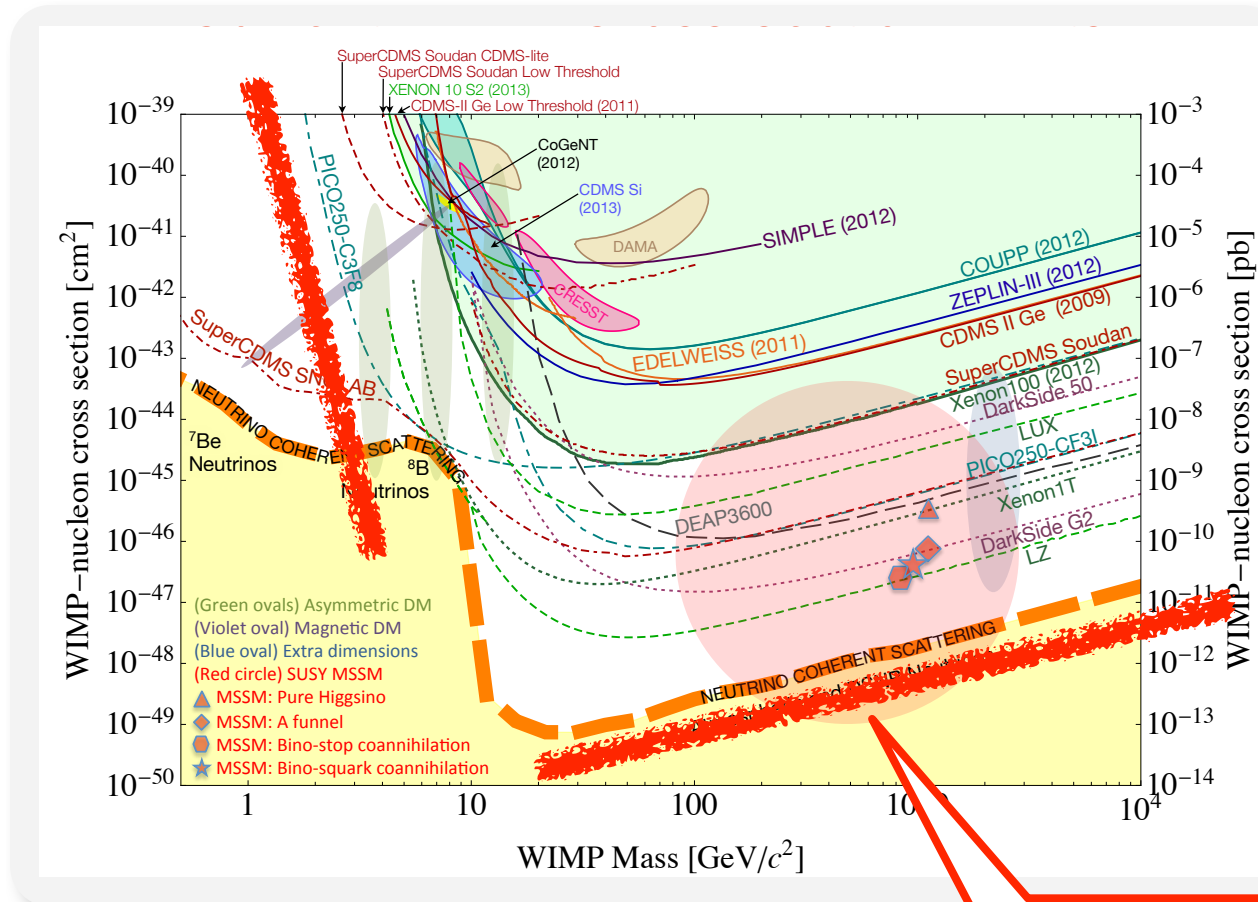
LUX collaboration, 2013



O(100) GeV DM,
typical DM range

Direct detection versus collider reach

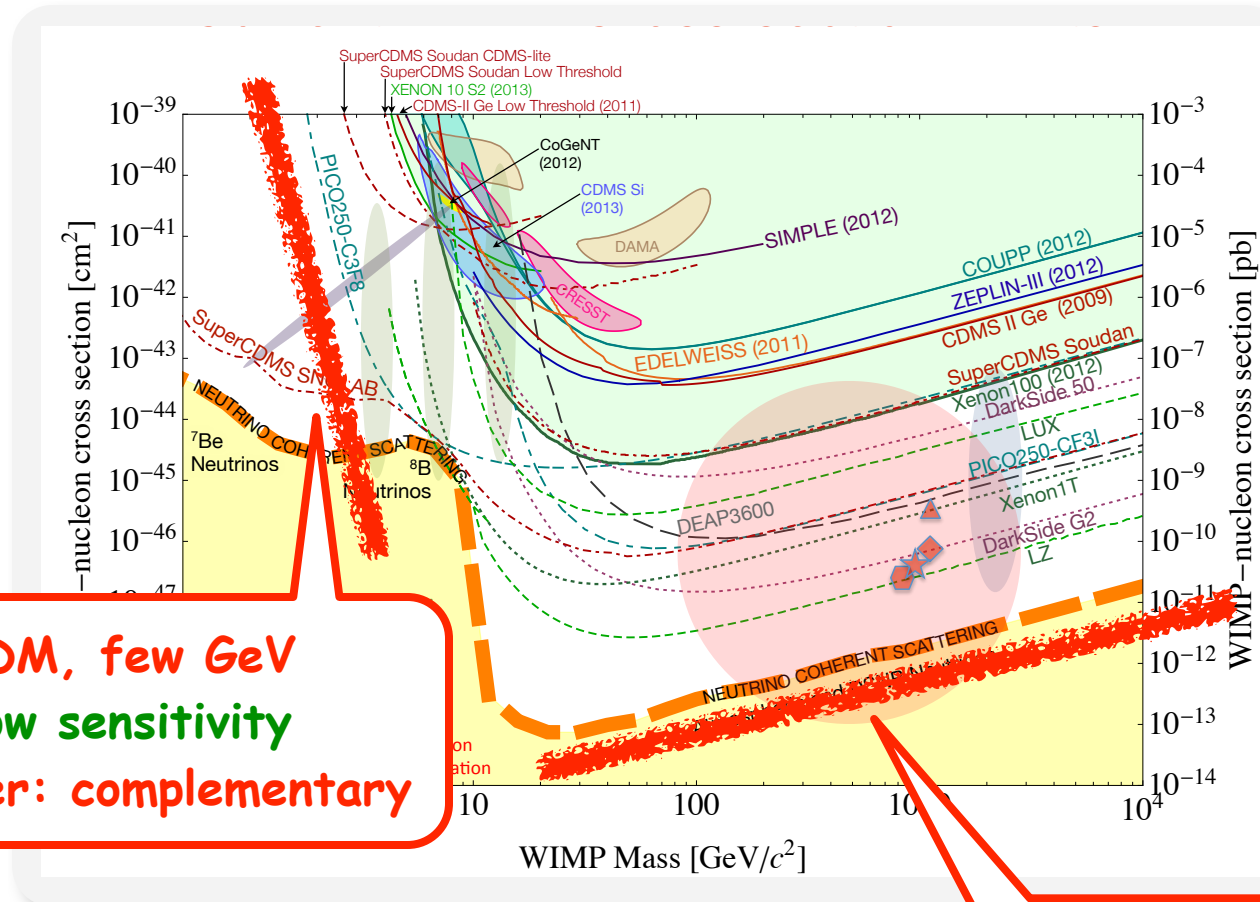
LUX collaboration, 2013



O(100) GeV DM,
typical DM range

Direct detection versus collider reach

LUX collaboration, 2013



light DM, few GeV
DD: low sensitivity
Collider: complementary

$O(100) \text{ GeV}$ DM,
typical DM range

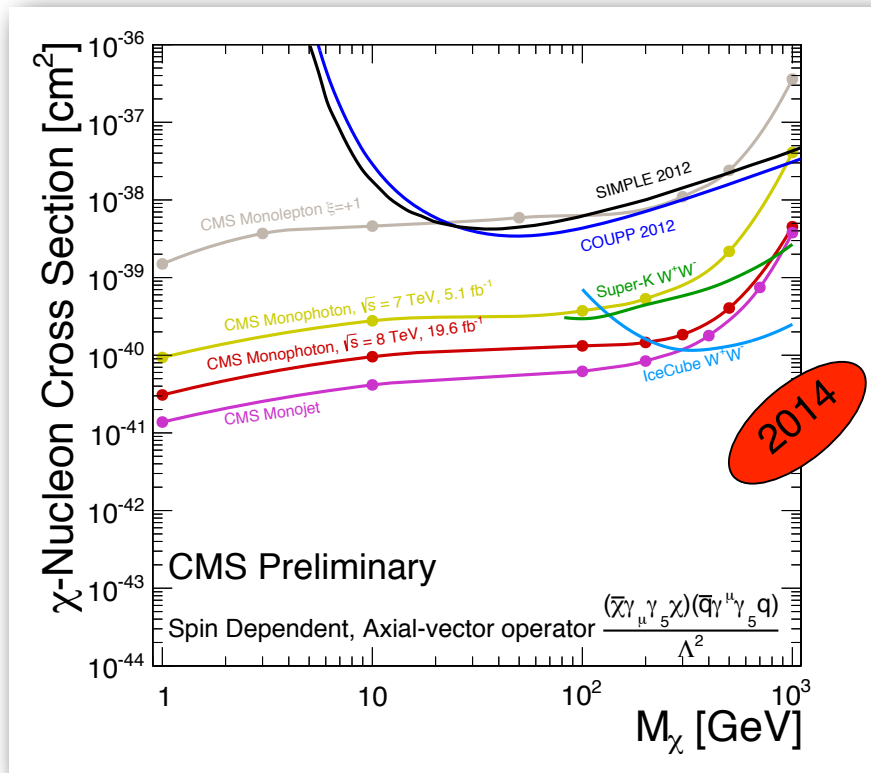
LHC/100 TeV: Higgs

SUSY and BSM Highlights from the LHC

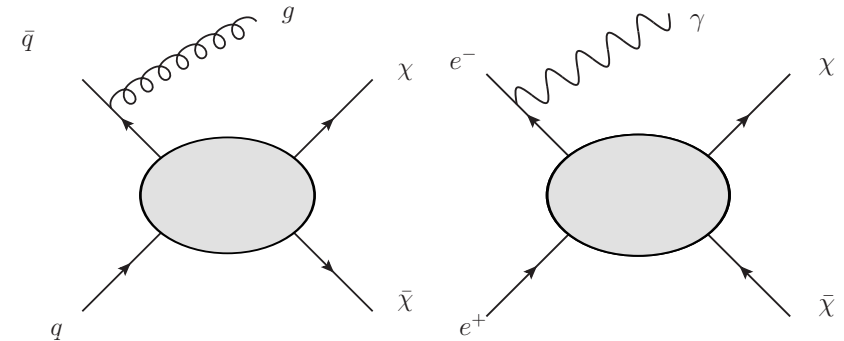
James PILCHER (University of Chicago)

Dark Matter, WIMPS or Axions

Prof. Liantao Wang (University of Chicago)



CMS PAS EXO-12-047

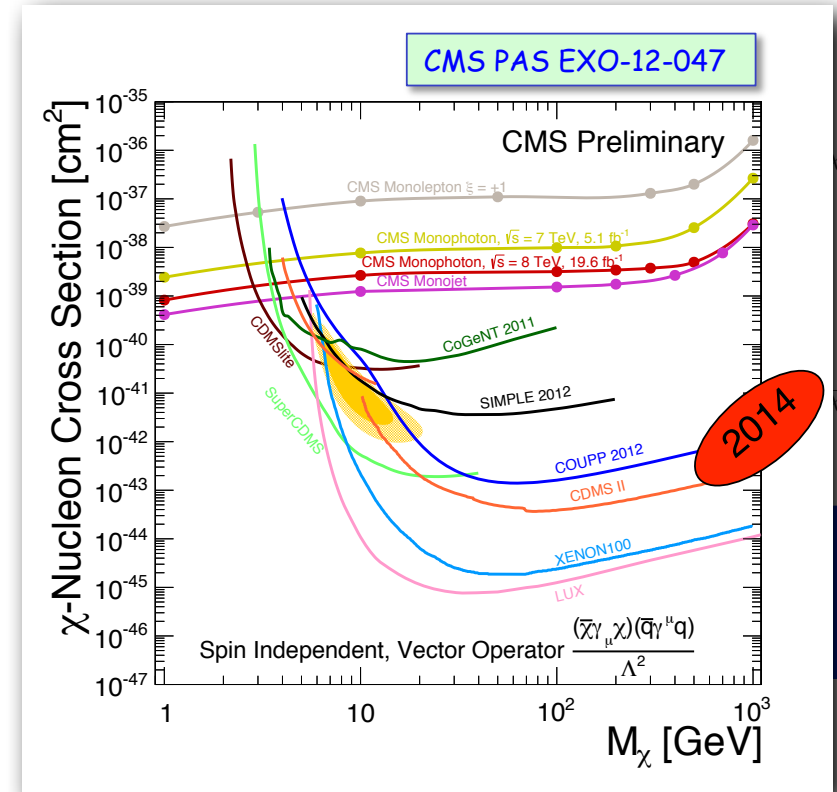
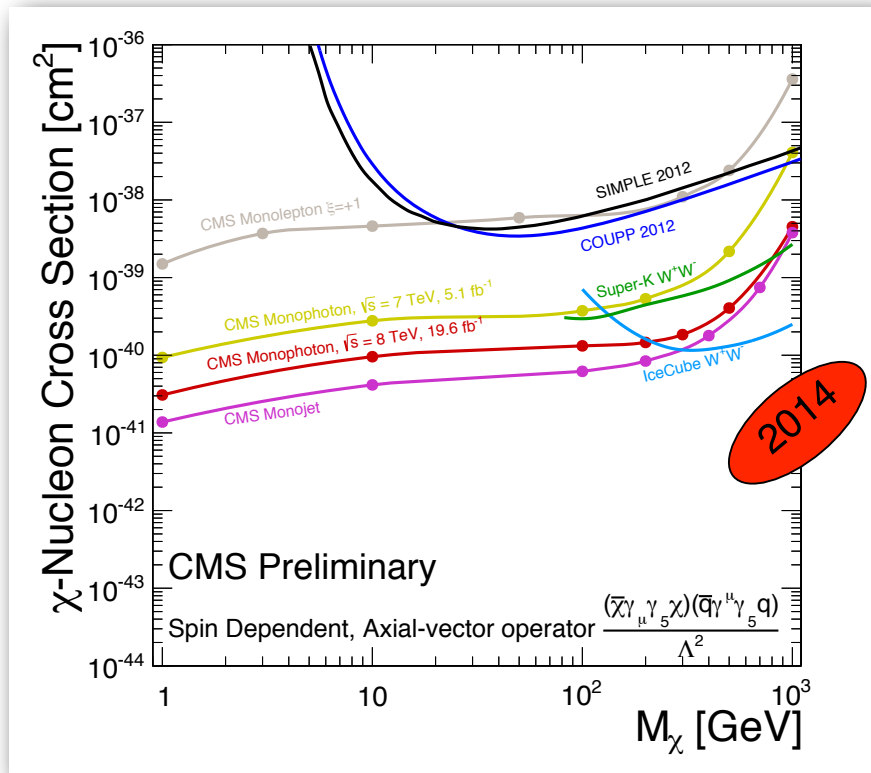


monojet, monophoton, monoZ,
monoW, mono-b, ...

LHC/100 TeV: Higgs

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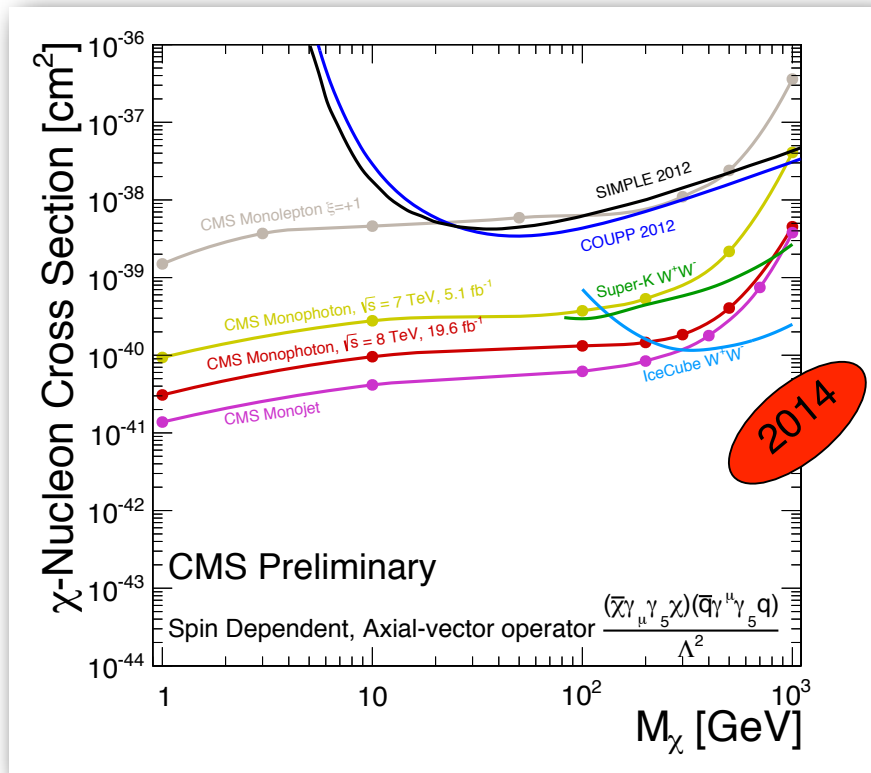


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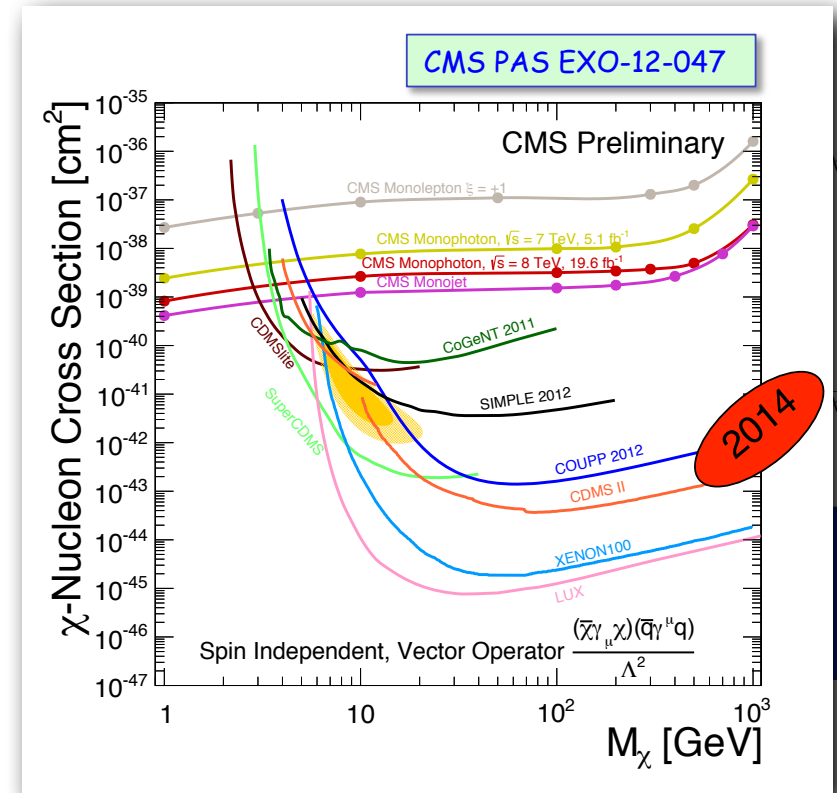
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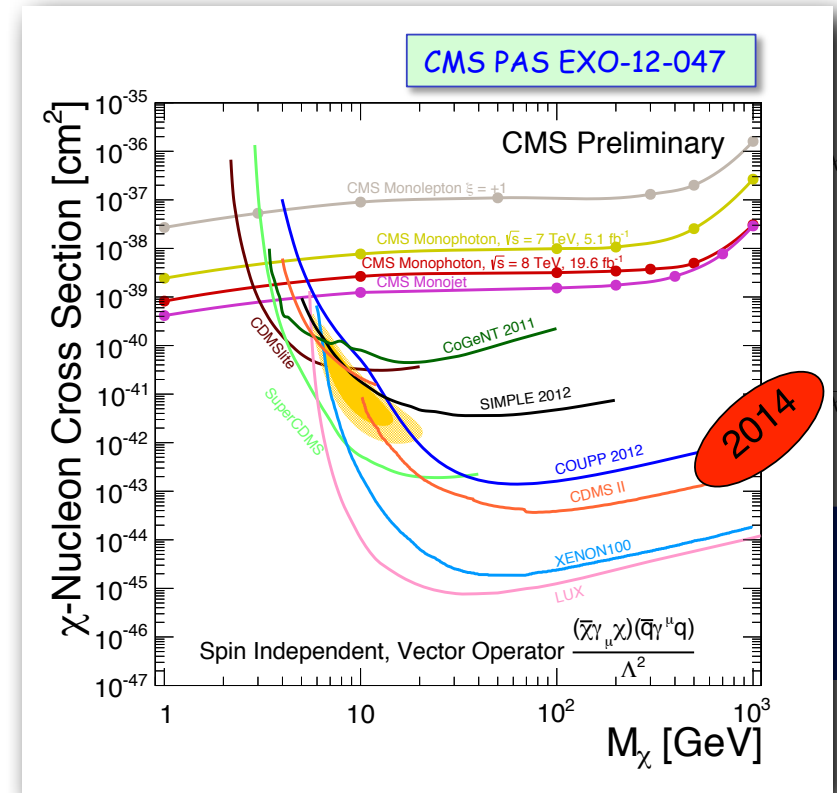
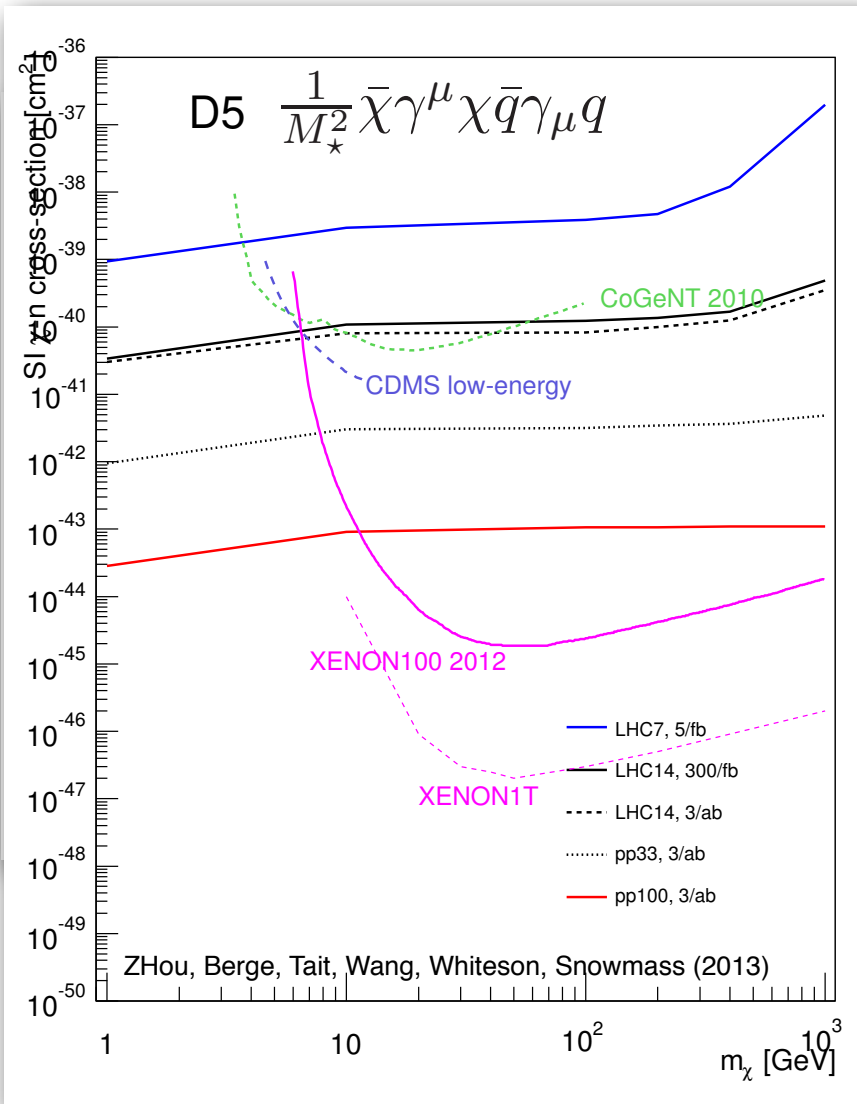


Collider better:
small m_χ region, spin-dependent

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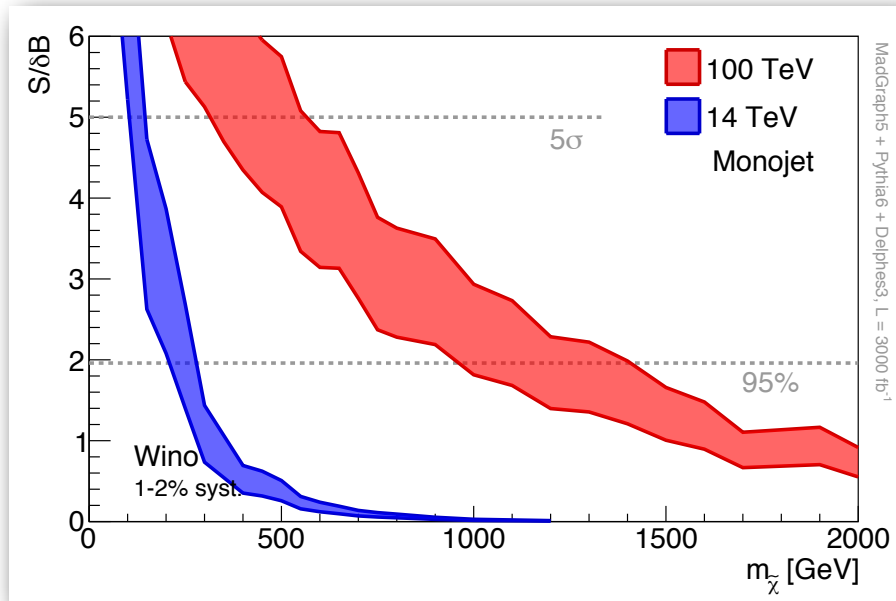
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LHC/100 TeV: MSSM DM

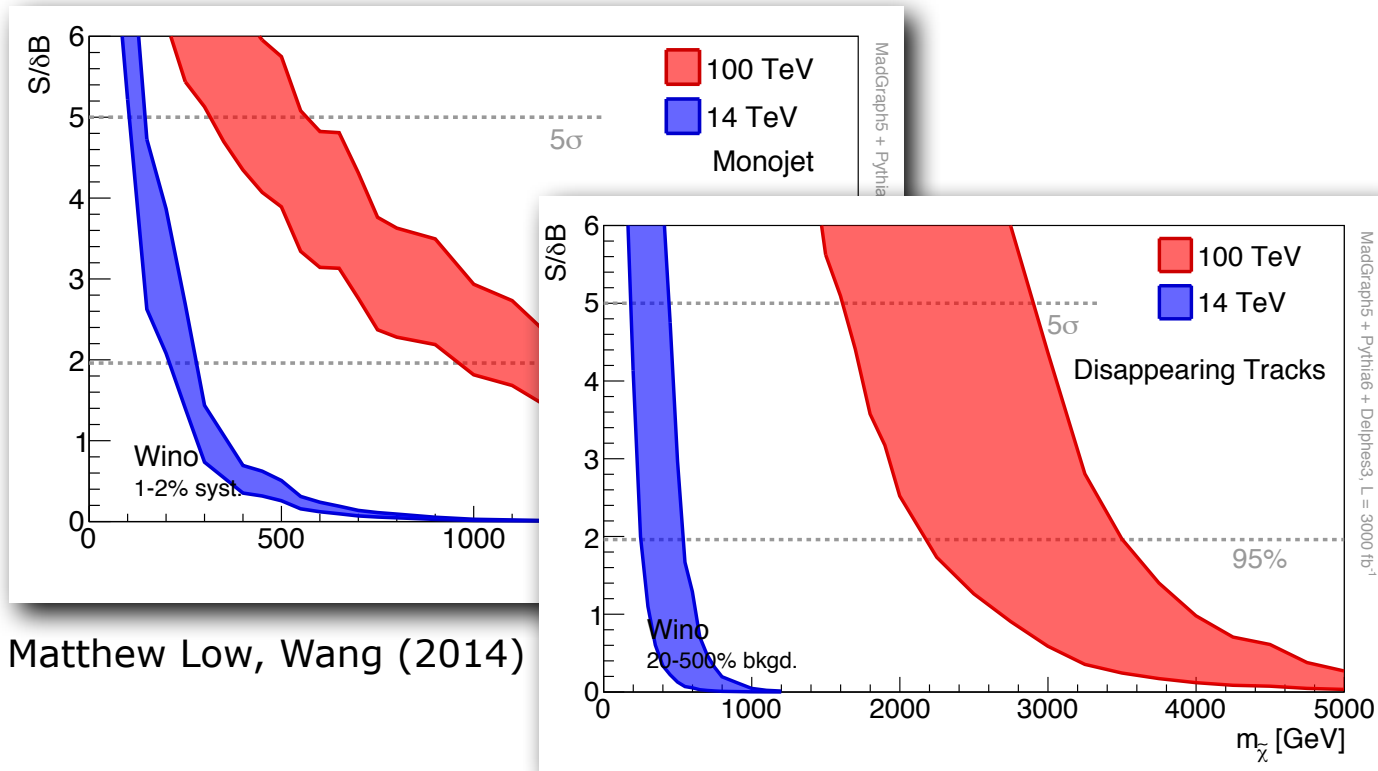
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Matthew Low, Wang (2014)

LHC/100 TeV: MSSM DM

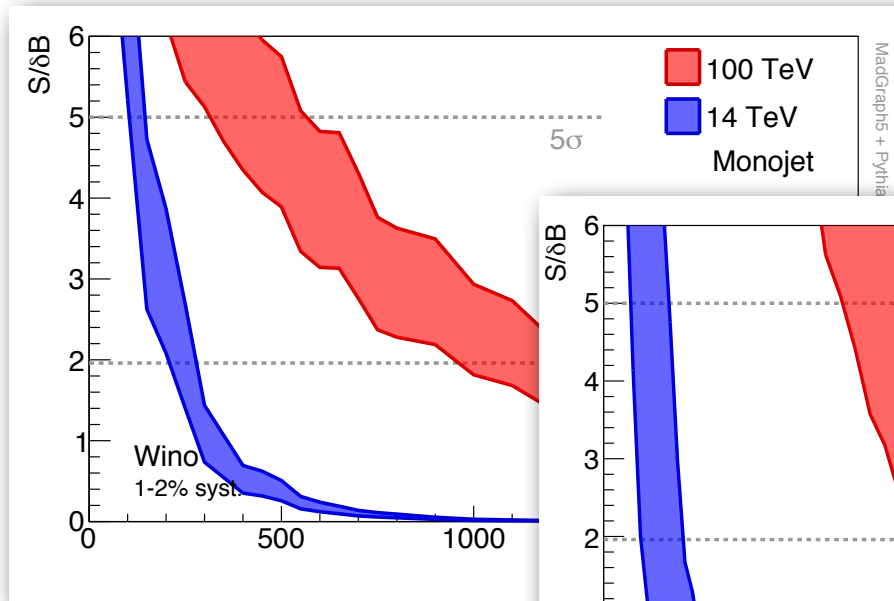
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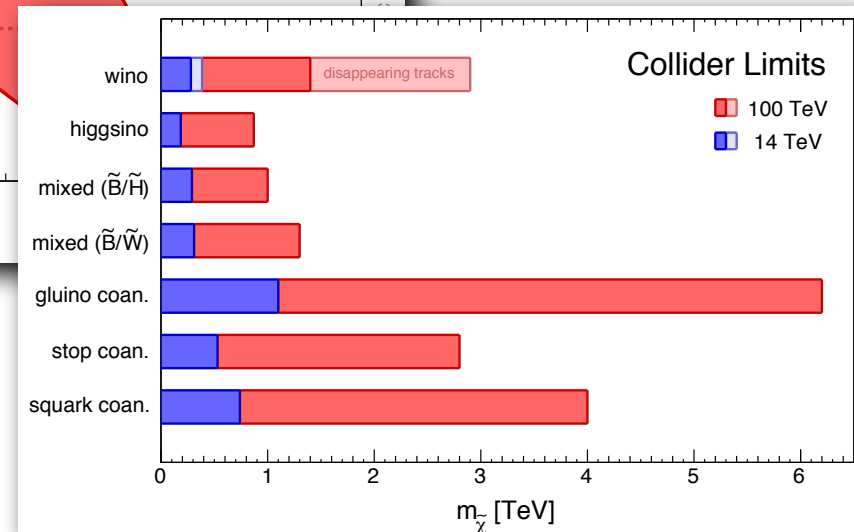
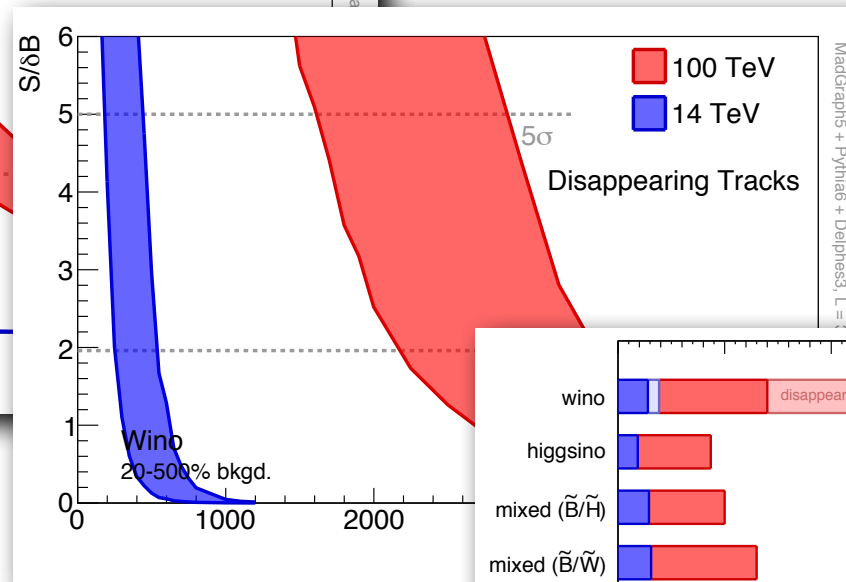
Matthew Low, Wang (2014)

LHC/100 TeV: MSSM DM

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Prof. Liantao Wang (University of Chicago)

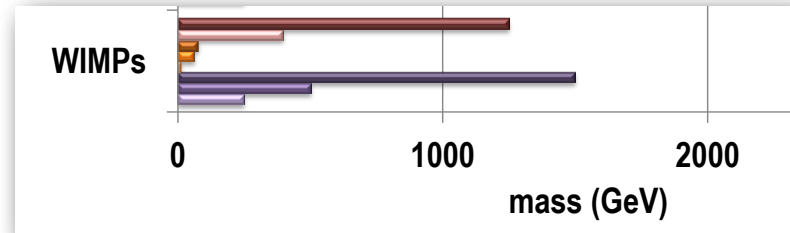


Matthew Low, Wang (2014)



Dark Matter

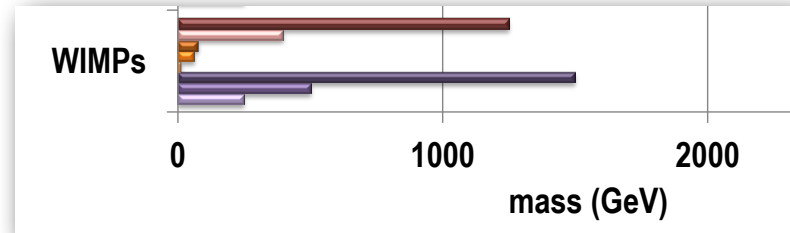
$$m_{\text{WIMP}} \leq 2 \text{ TeV} \left(\frac{g_{\text{eff}}^2}{0.3} \right)$$



- ◎ Dark matter at TeV scale (Wino or Higgsino LSP)
 - can not be explored at LHC 14 with 300 fb⁻¹
 - enhanced reach at VLHC 33 or 100 TeV
- ◎ Smaller dark matter mass
 - low mass loopholes of suppressed coupling or compressed spectrum, small MET
 - e⁺e⁻ collider, reach E_{cm}/2.

Dark Matter

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SUSY Electrowinos including Higgs in the final state

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Dark Matter, WIMPs or Axions

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Vector boson productions associated with new physics (VBF)

Prof. Bhaskar Dutta (Texas A&M University)

Searches for New Particles

Searches for New Particles

- ◎ strong interacting particles

gluinos, squarks

- ◎ EW interacting particles

electroweakinos: $(W/Z/h)(W/Z/h)+\text{MET}$ final states

sleptons: reach depends on LSP type

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High-mass states decaying to $t\bar{t}$ in fully boosted regime at a 100 TeV collider

Sergei Chekanov (ANL)

Ratios and characteristic distributions in the search for deviation from the SM productions, Dr. David Curtin (Stony Brook)

Colored resonances, Dr. Felix Yu (Fermilab)

Boosted SM topologies and algorithms, Brock Tweedie (University of Pittsburgh)

Composite Higgs, Giuliano Panico (CERN & ETH Zurich)

Zprime at 100 TeV Collider, Zhen Liu (University of Pittsburgh)

SUSY and BSM Highlights from the LHC, James PILCHER (University of Chicago)

Prospects of New Physics searches using HL-LHC, Altan Cakir (DESY)

Searches for New Particles

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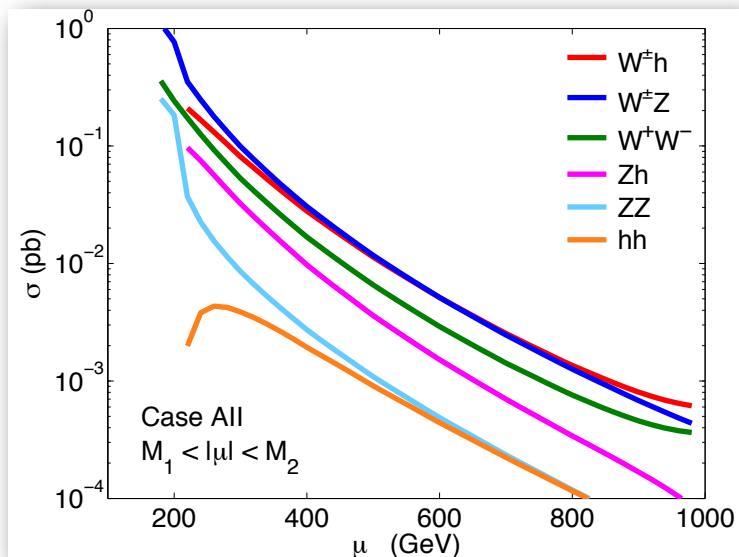
 - gluinos, squarks

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... in fully boosted regime at a 100 TeV collider

... in the search for deviation from the SM

(Brook)

(Fermilab)

... by CMS, Brock Tweedie (University of Pittsburgh)

... by ATLAS, ETH Zurich)

... by LHC, James PILCHER (University of Chicago)

... by HL-LHC, Altan Cakir (DESY)

Searches for New Particles

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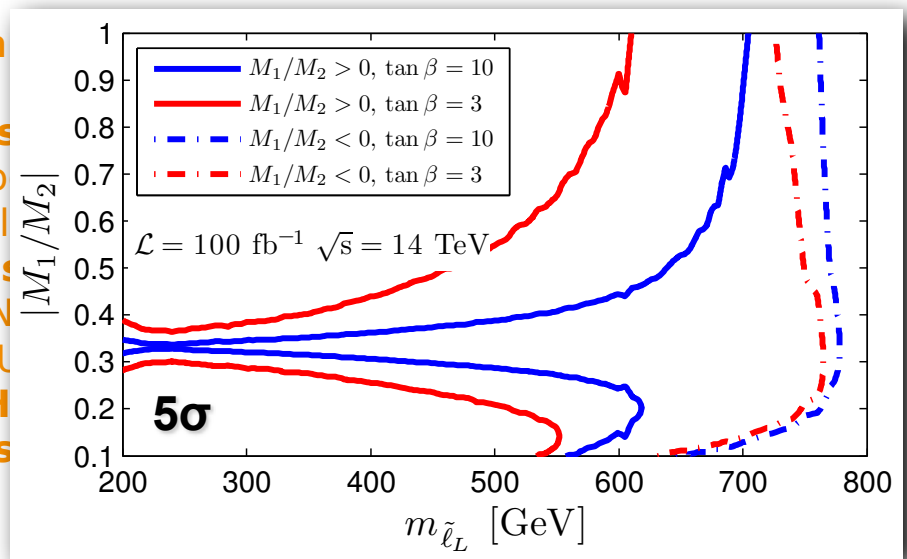
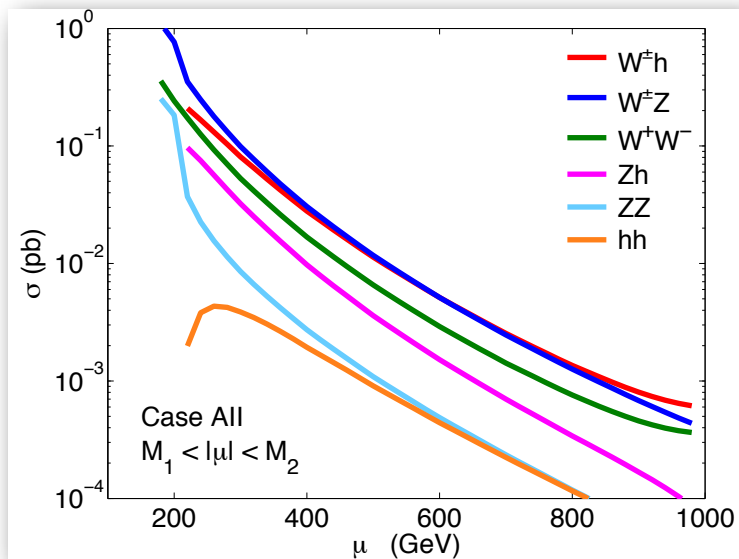
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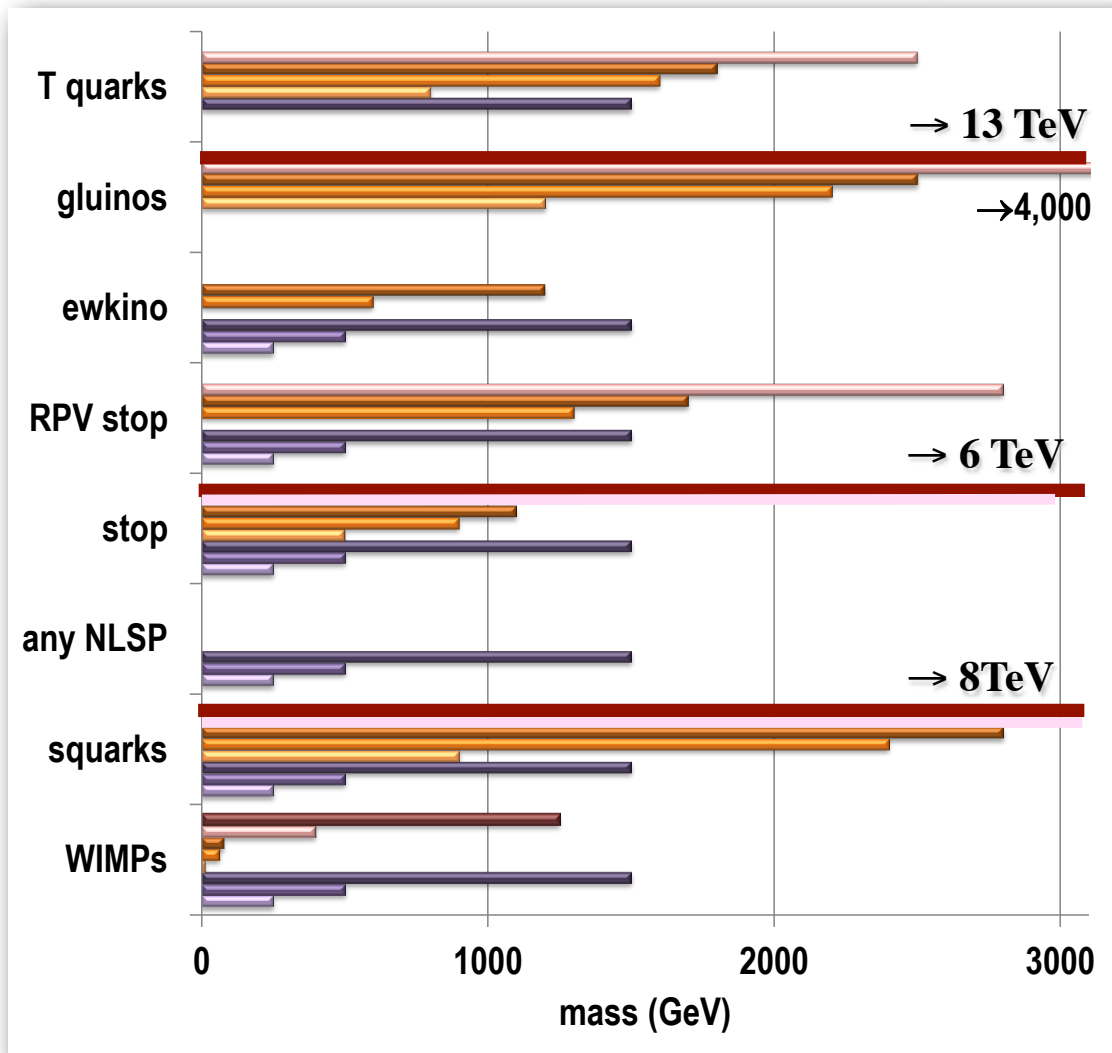
sleptons: reach depends on LSP type

...

Eckel, Ramsey-Musolf, Shepherd, Su (2014)



BSM: Collider Reach



pp, 100 TeV, 3000/fb

pp, 33 TeV, 3000/fb

pp, 14 TeV, 3000/fb

pp, 14 TeV, 300/fb

pp, 8 TeV, 20/fb

ee, 3 TeV, 1000/fb

ee, 1 TeV, 1000/fb

ee, 0.5 TeV, 500/fb

energy versus precision

pp: blind spot

LC: mass limited, $E_{\text{cm}}/2$

Cosmo connection

baryogenesis, phase transition

Electroweak baryogenesis, Patrick Meade (Stony Brook)

Conclusion

- ◎ the discovery of Higgs is a remarkable triumph in particle physics
- ◎ a light weakly coupled Higgs argues for new physics beyond SM
- ◎ Search for new physics calls for both high precision machine and high energy machine
- ◎ HL-LHC: probe Higgs precision few% (factor of 2 increase), search for new physics limited (20% increase)
- ◎ 100 TeV pp machine:
 - probe energy frontier: BSM Higgs, naturalness connection, dark matter
 - precision, H coupling, H^3, H^4, V^3, V^4 couplings (cosmo connection)
- ◎ FCC-ee/hh, CEPC/SPPC, ILC/CLIC...

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An exciting journey ahead of us!

Conclusion

An exciting journey ahead of us!

Conclusion



LHC

An exciting journey ahead of us!

Conclusion



LHC



HL-LHC

An exciting journey ahead of us!

Conclusion



LHC



HL-LHC



100 TeV pp

An exciting journey ahead of us!

Conclusion



LHC



HL-LHC



100 TeV pp



Lepton Collider

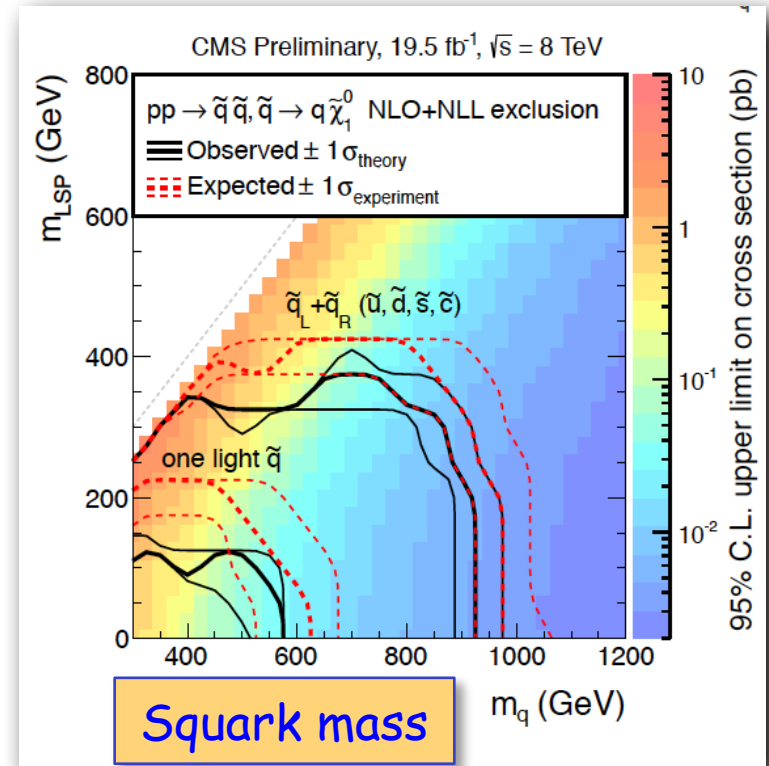
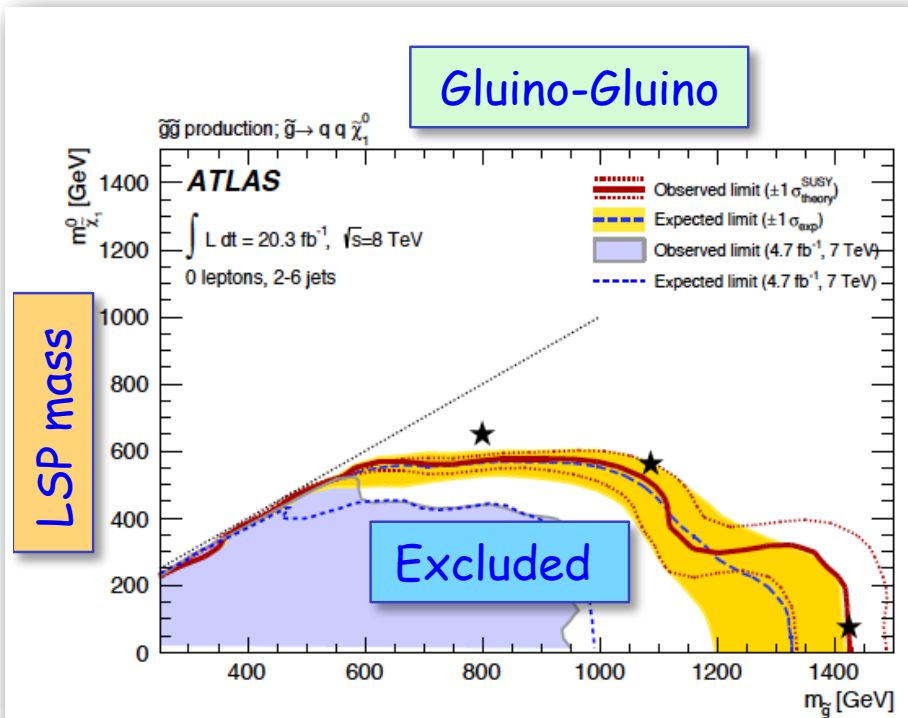
An exciting journey ahead of us!

BACKUP

Gluinos and Squarks

LHC (now): BSM

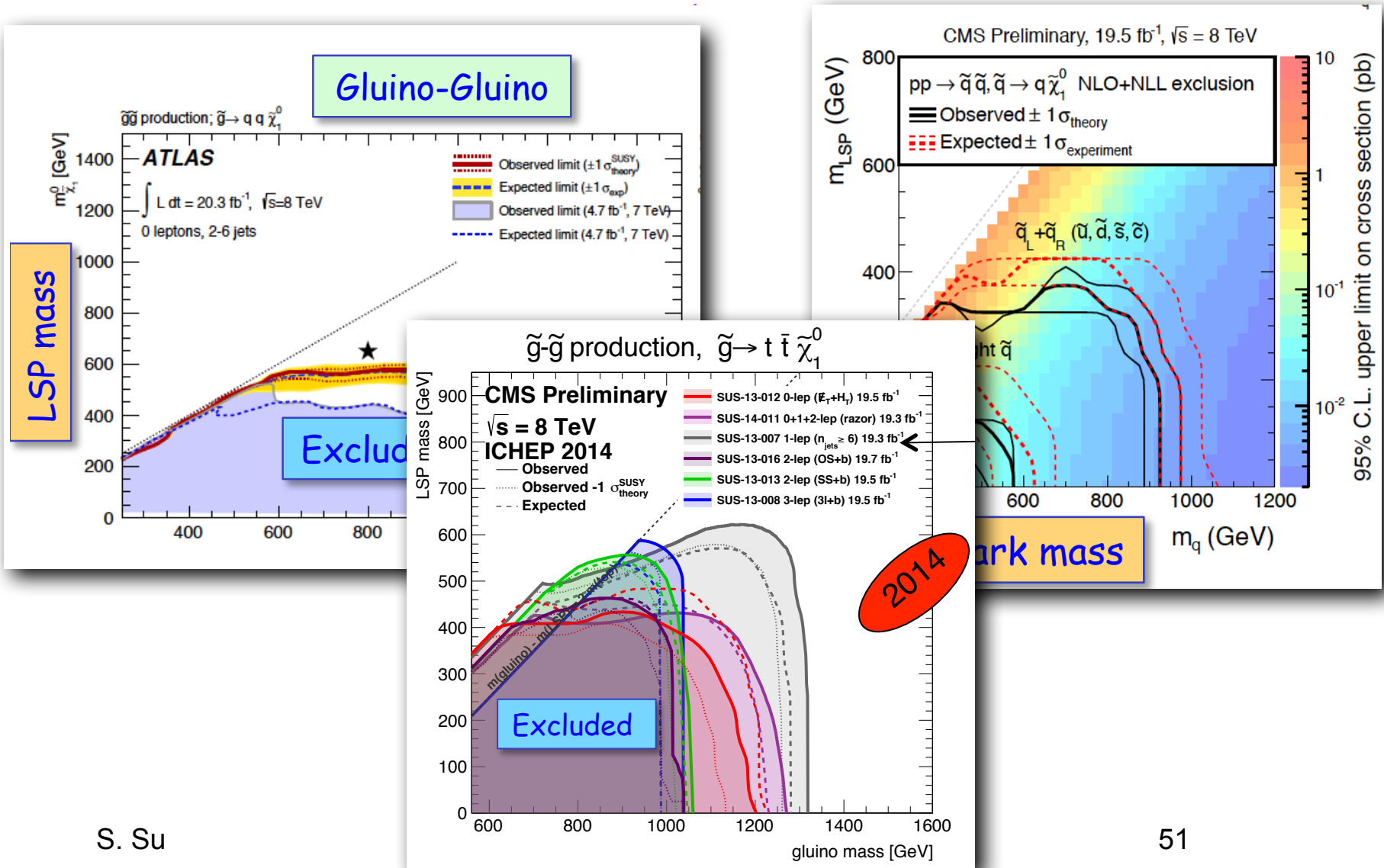
SUSY and BSM Highlights from the LHC
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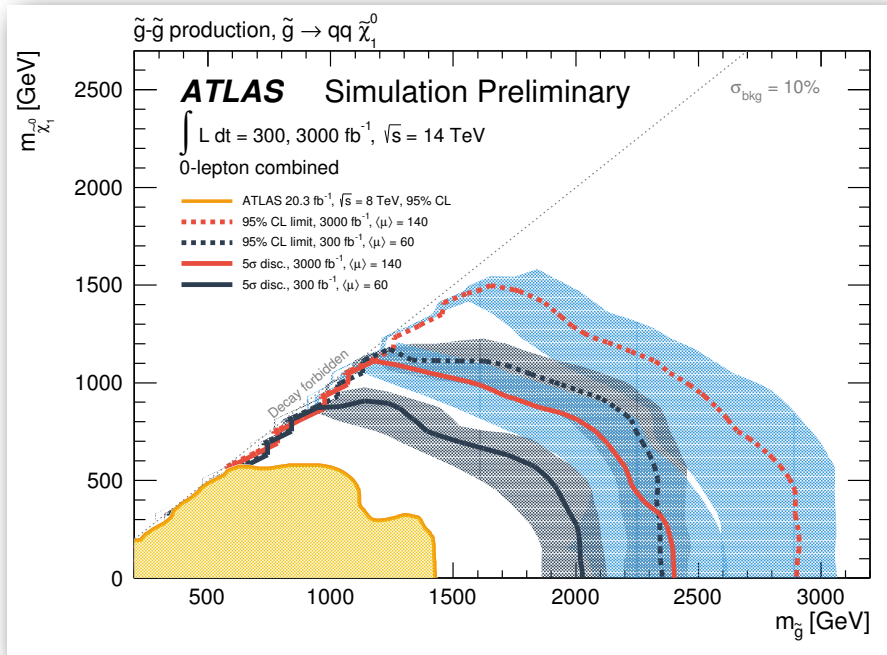
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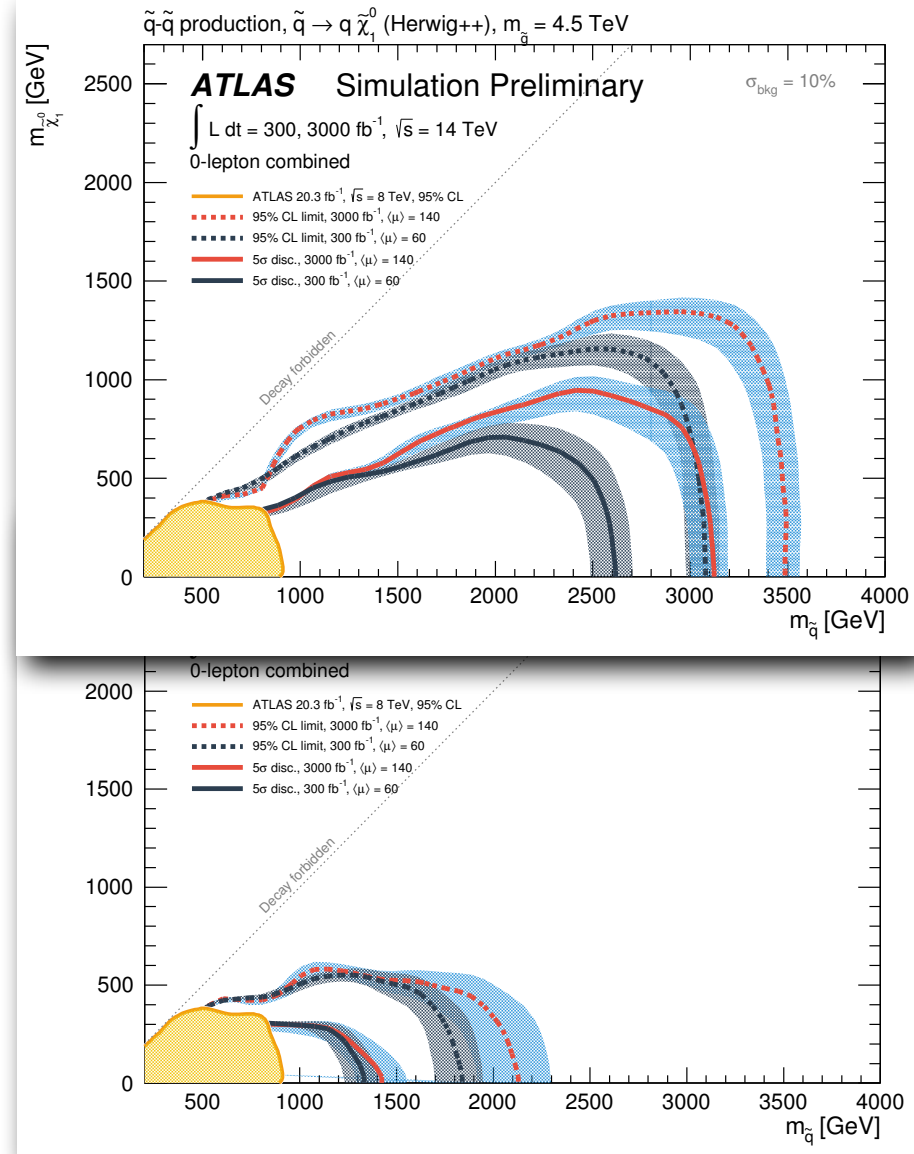
LHC/HL-LHC: gluino and squark

SUSY Colored production with gluinos and squarks, Mike Hance (LBNL)



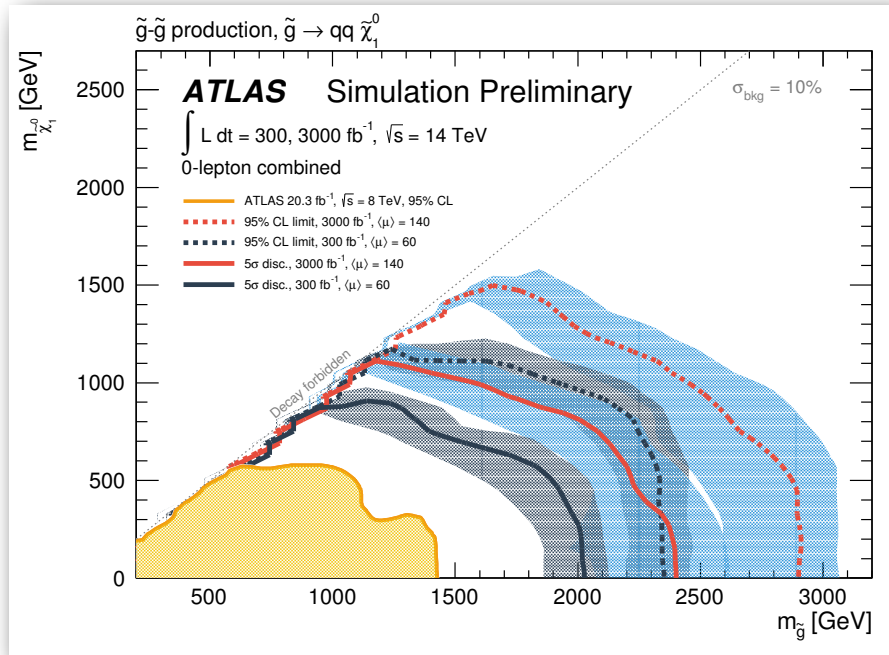
ATLAS-PUB-2014-010

S. Su



LHC/HL-LHC: gluino and squark

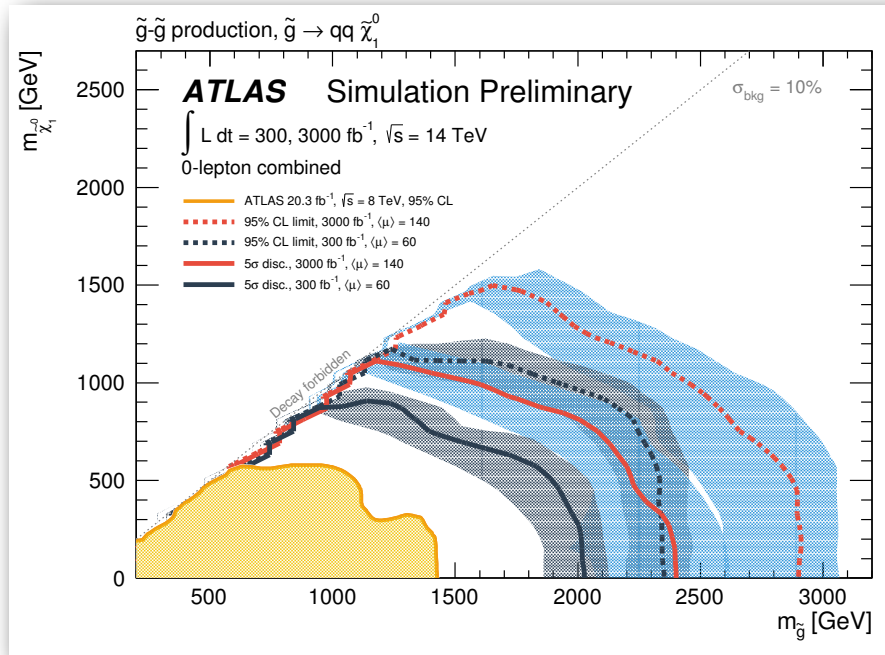
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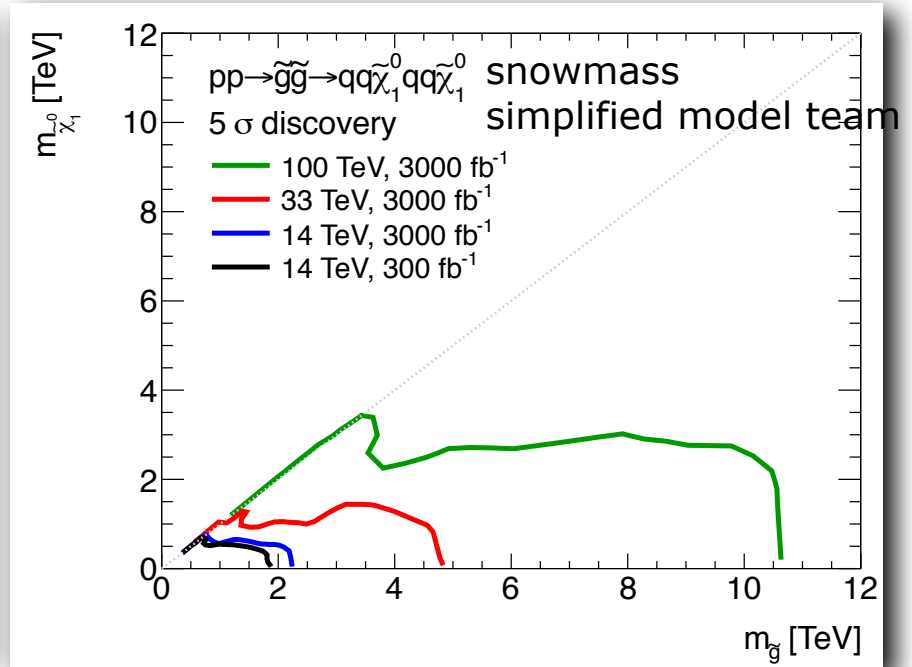
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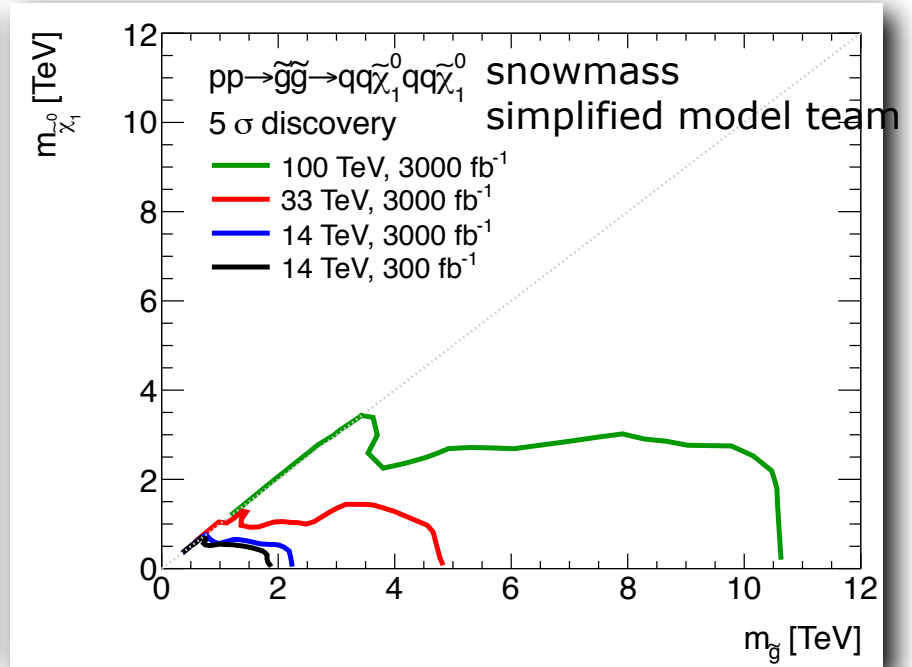
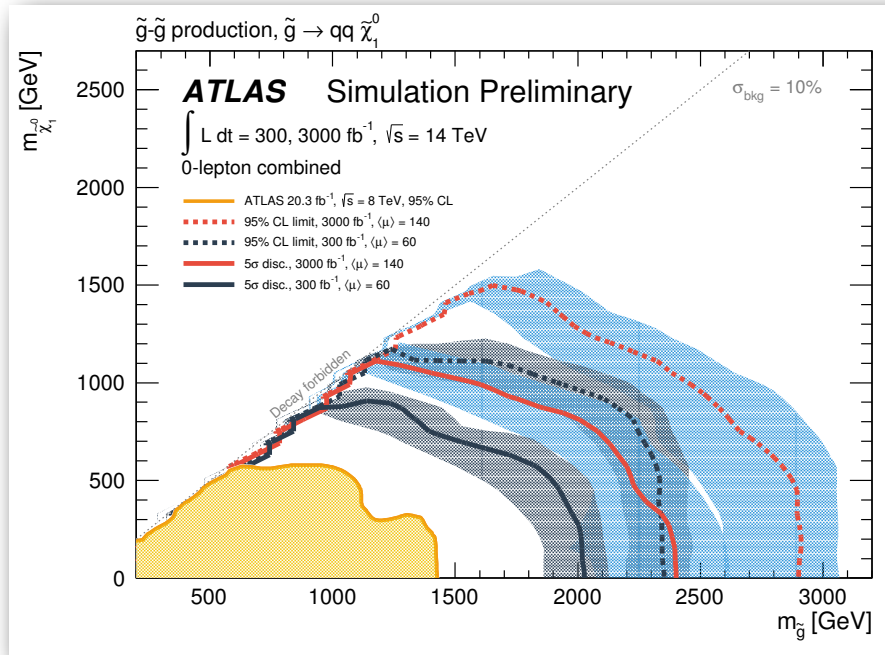


ATLAS-PUB-2014-010



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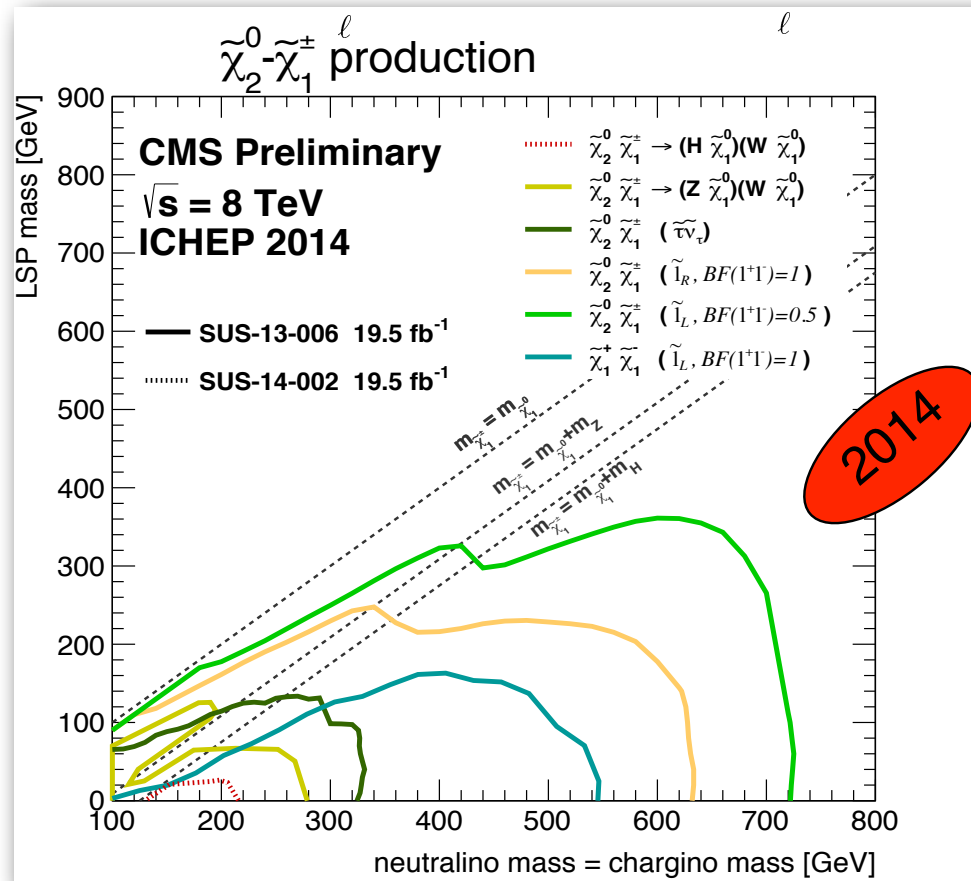


ATLAS-PUB-2014-010

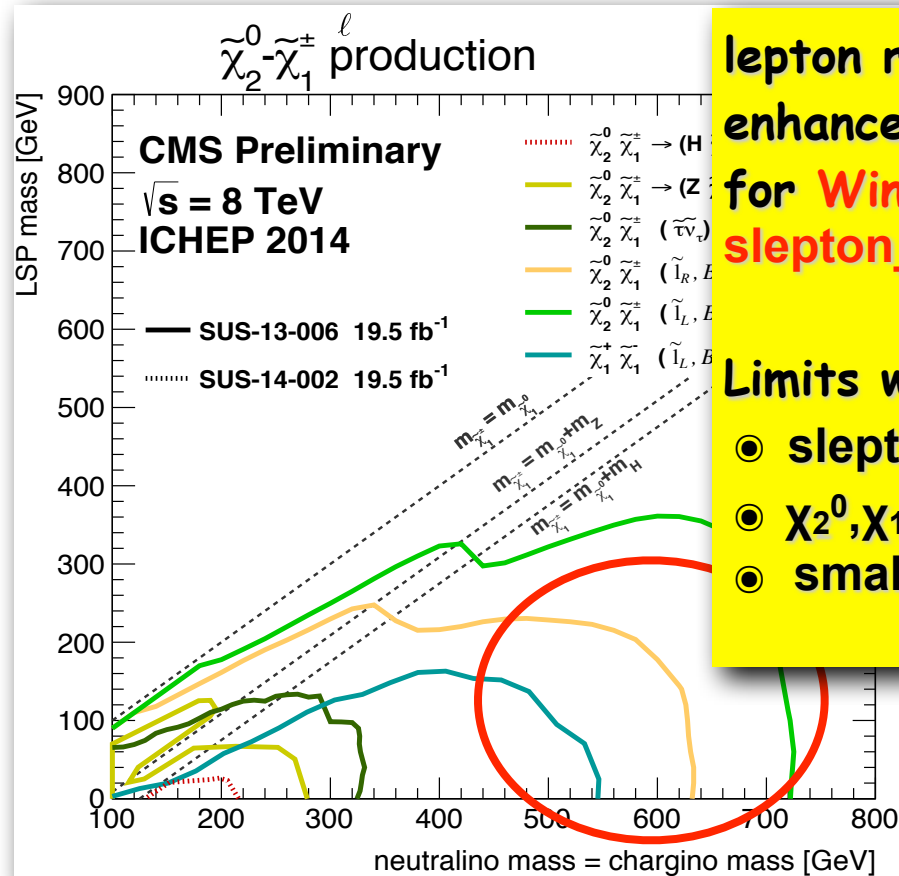
- Mass reach extended by a factor of 2 at 14 TeV, 300 fb^{-1}
- further extended by 20% at 3 ab^{-1}
- If no excess seen at 300 fb^{-1} , can not be seen at 3 ab^{-1}
- 100 TeV pp: increase the reach by a factor of 5.

Neutralinos and Charginos

LHC (now): Neutralino/Chargino



LHC (now): Neutralino/Chargino

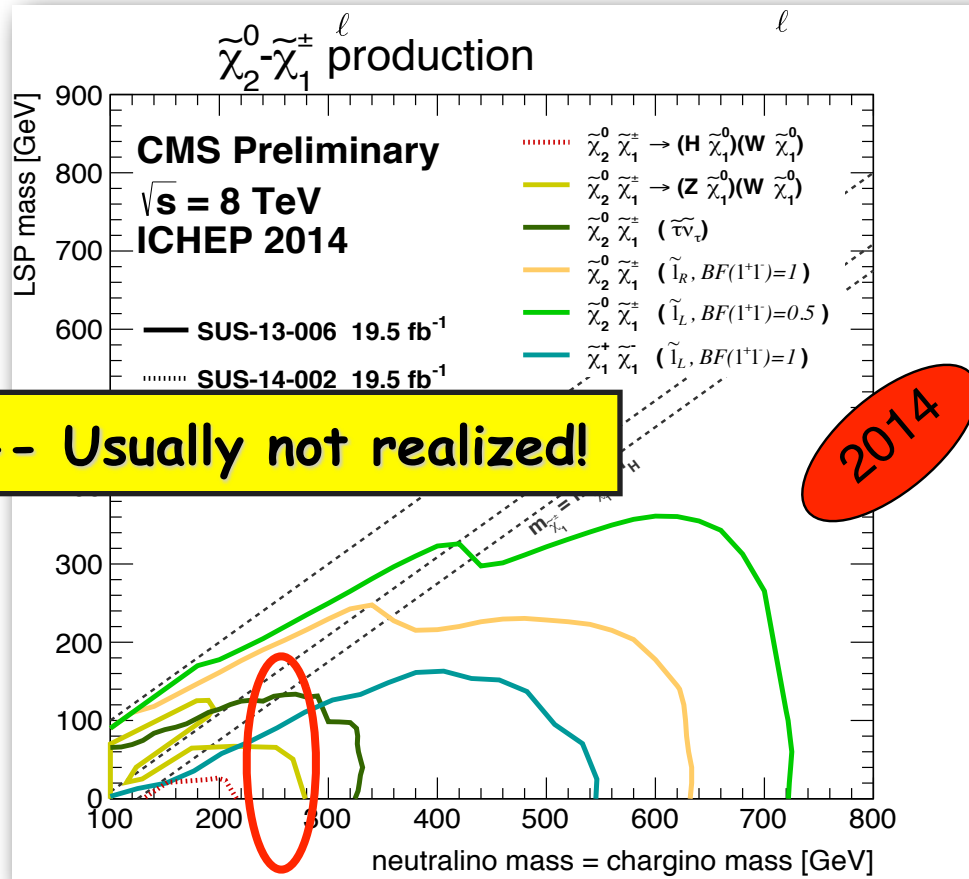


lepton rich final states to enhance reach: only works for **Wino NLSP** with light **slepton_L**.

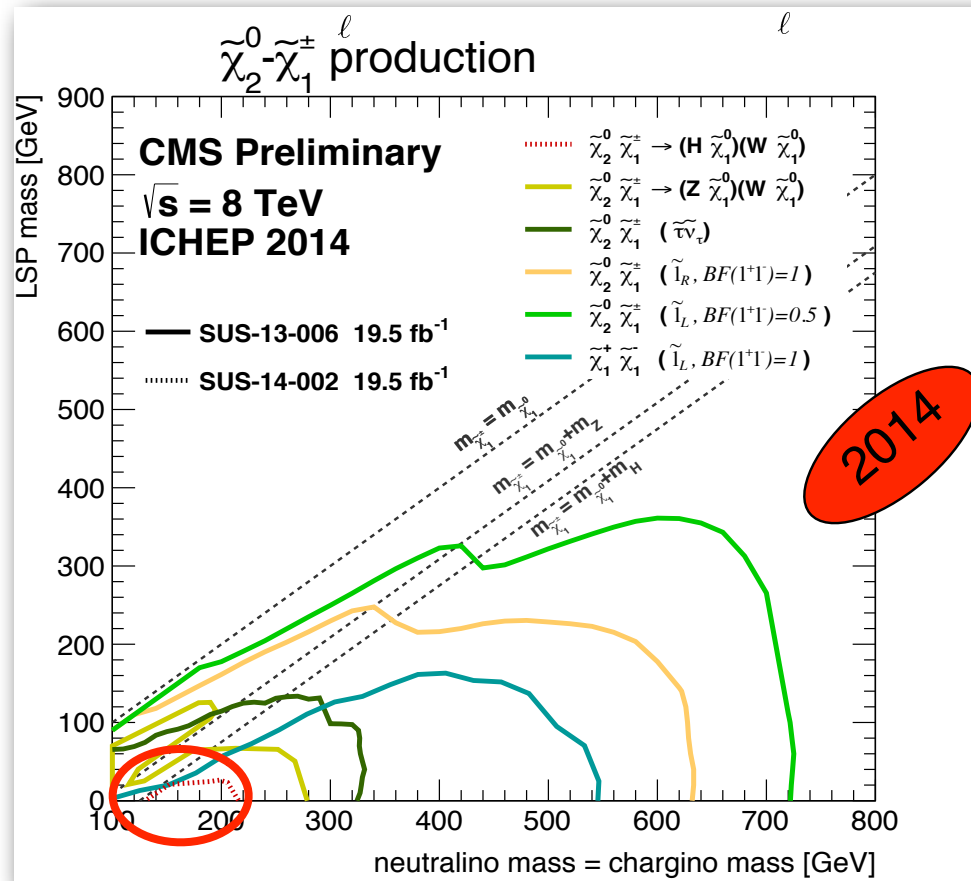
Limits weaker for

- slepton_L heavy
- χ_2^0, χ_1^\pm being Higgsinos
- small $m_{\chi_1^\pm} - m_{\chi_1^0}$

LHC (now): Neutralino/Chargino



LHC (now): Neutralino/Chargino



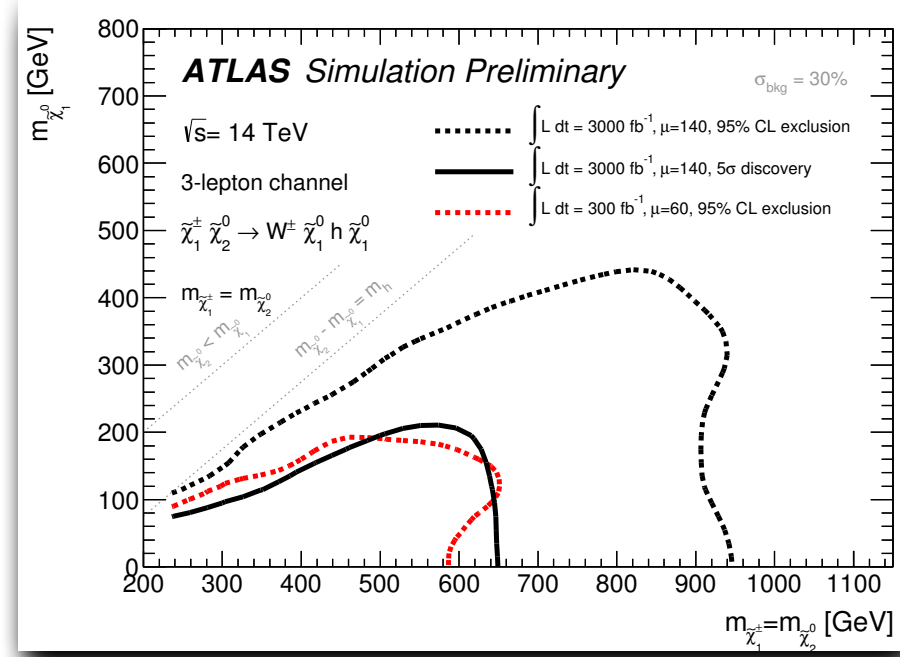
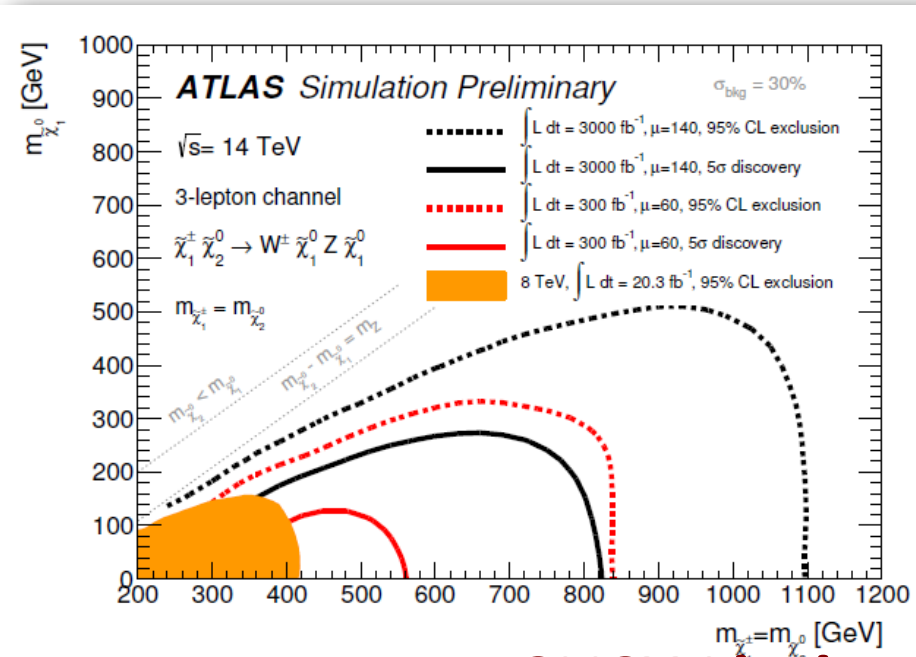
A rich mixture of (W/Z/h)(W/Z/h)+MET final states!

SUSY Electrowinos including Higgs in the final state
 Felix Kling

LHC/HL-LHC: Neutralino/Chargino

Prospects of New Physics searches using HL-LHC, Altan Cakir (DESY)

ATLAS-PUB-2014-010

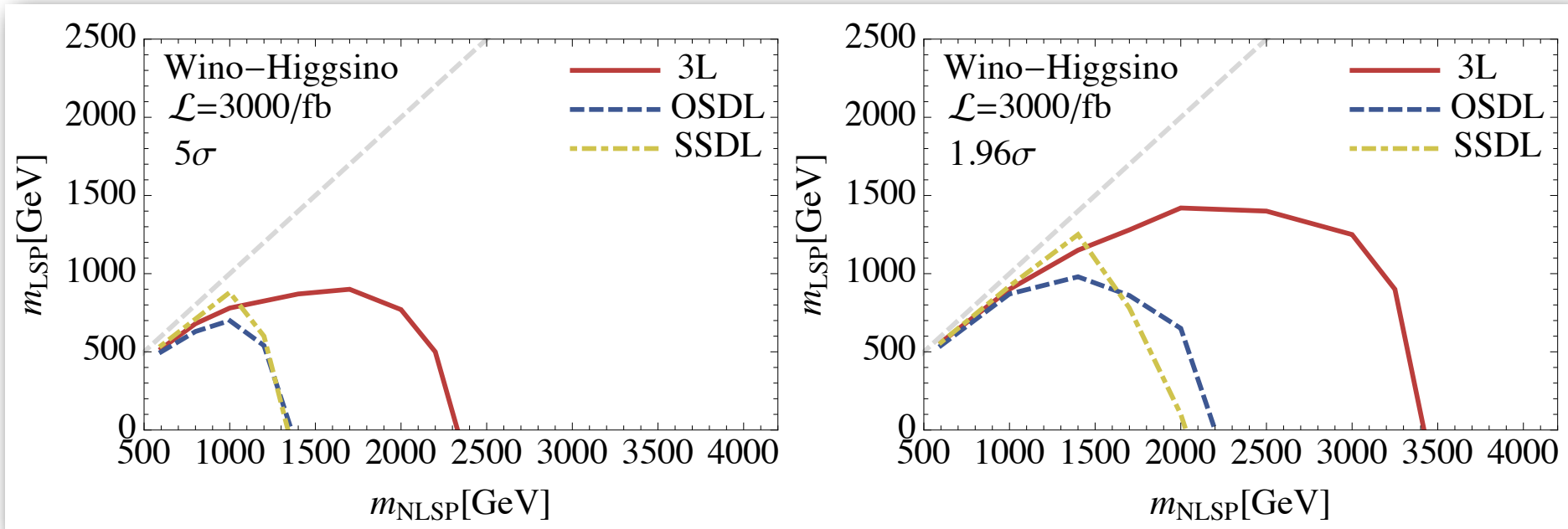


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100 TeV pp: Neutralino/Chargino

100 TeV pp

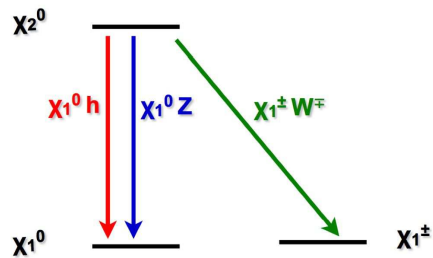
Dark Matter, WIMPS or Axions
Prof. Liantao Wang (University of Chicago)



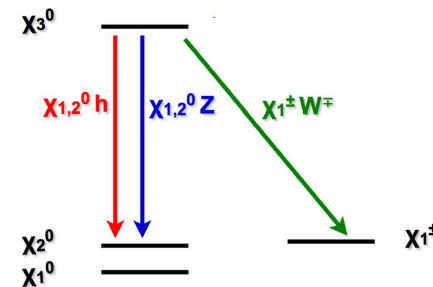
VBF production becomes more important at 100 TeV pp as well.

Neutralino/Chargino: Compressed

Case BI



Case CI



NLSP production suppressed.

**Compressed spectrum,
nearly degenerate LSP pair productions**

ILC: Unique opportunity, MET+Initial State radiation.

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Dark Matter, WIMPS or Axions

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Vector boson productions associated with new physics (VBF)

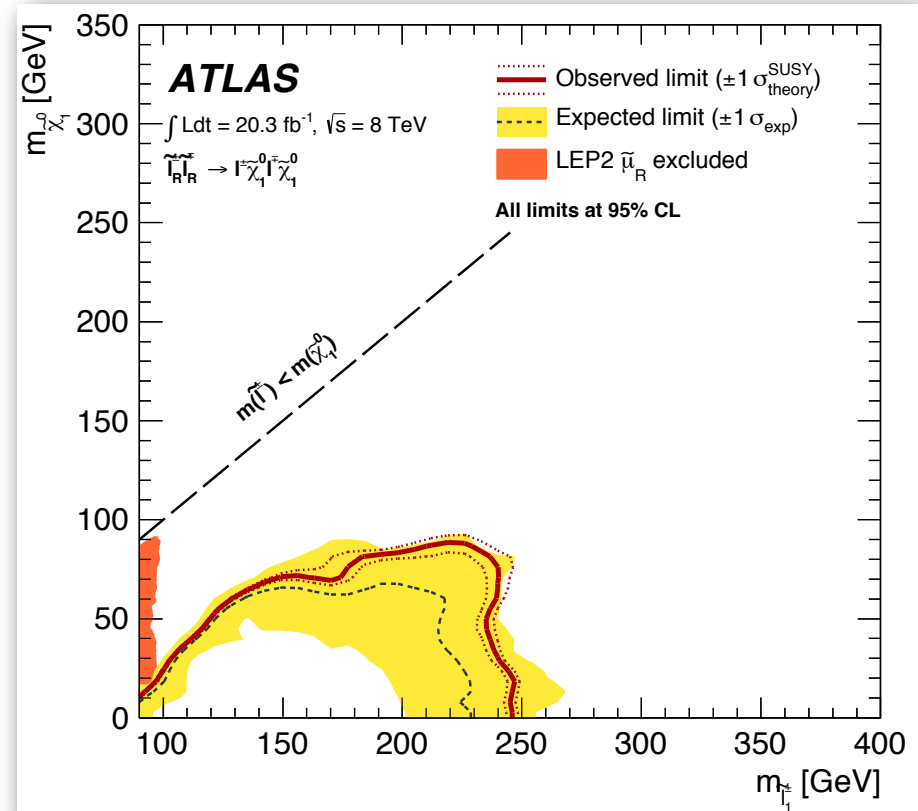
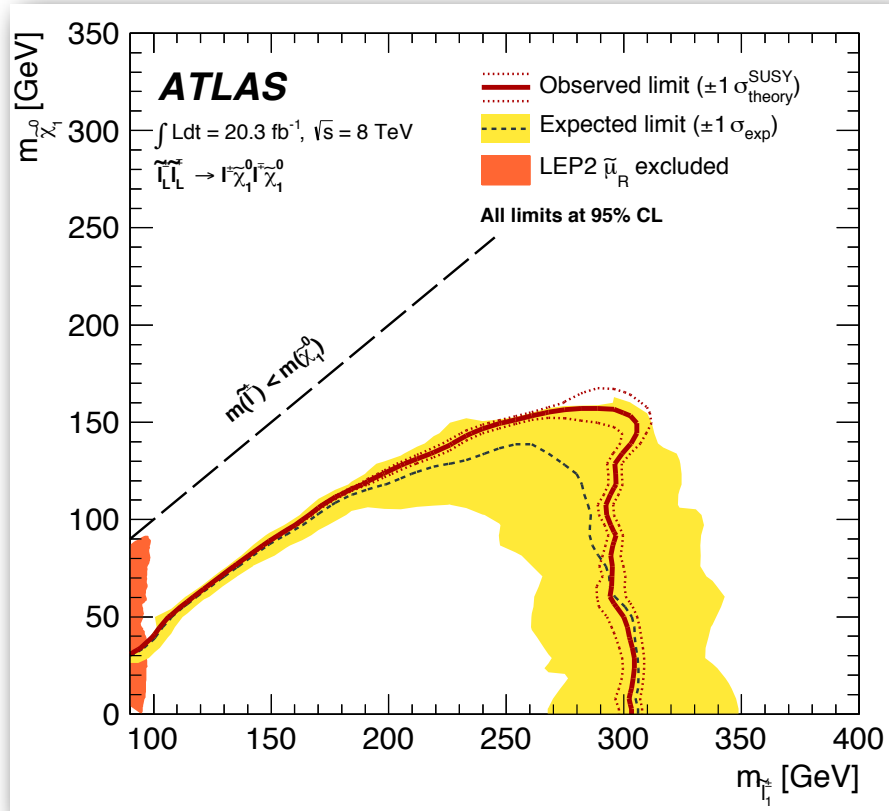
Prof. Bhaskar Dutta (Texas A&M University)

Sleptons

LHC (now): Sleptons

dilepton + MET

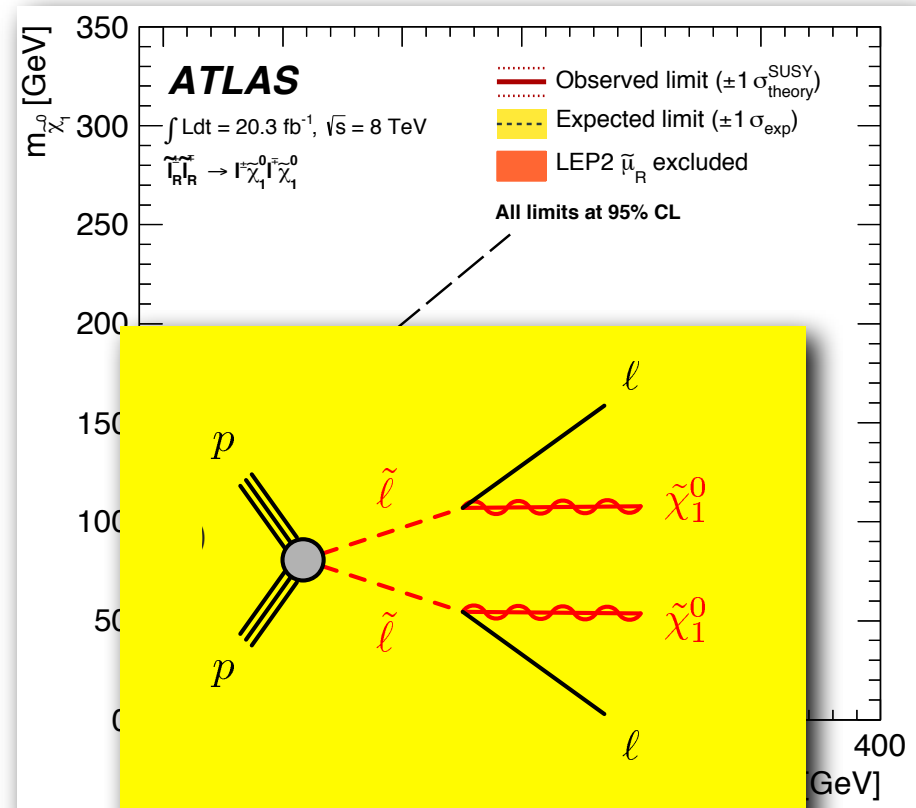
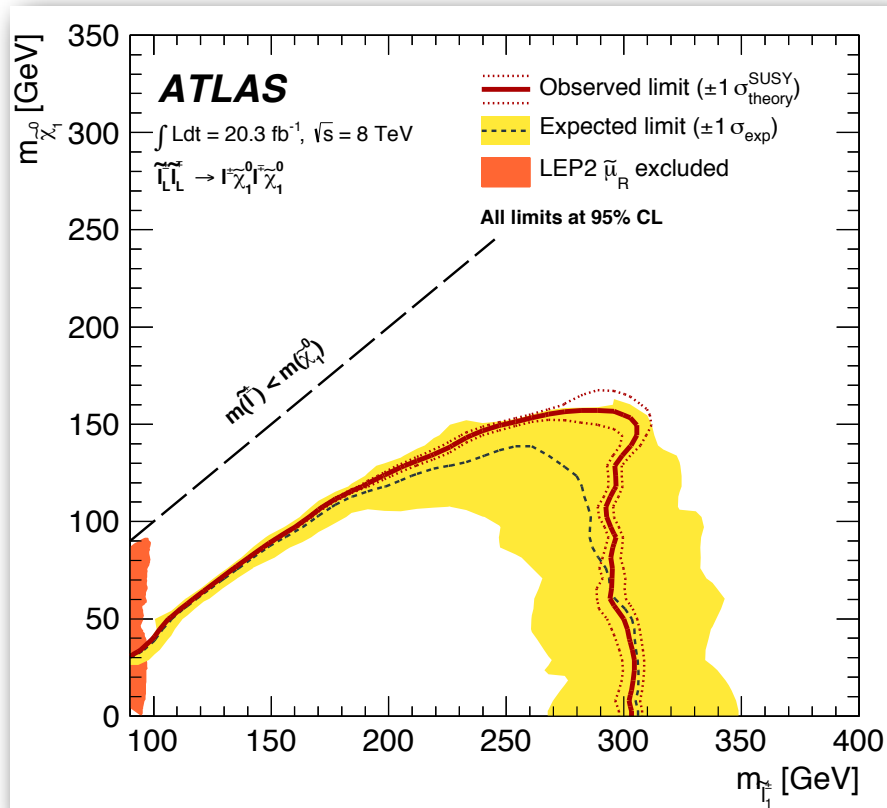
ATLAS, 1403.5294



LHC (now): Sleptons

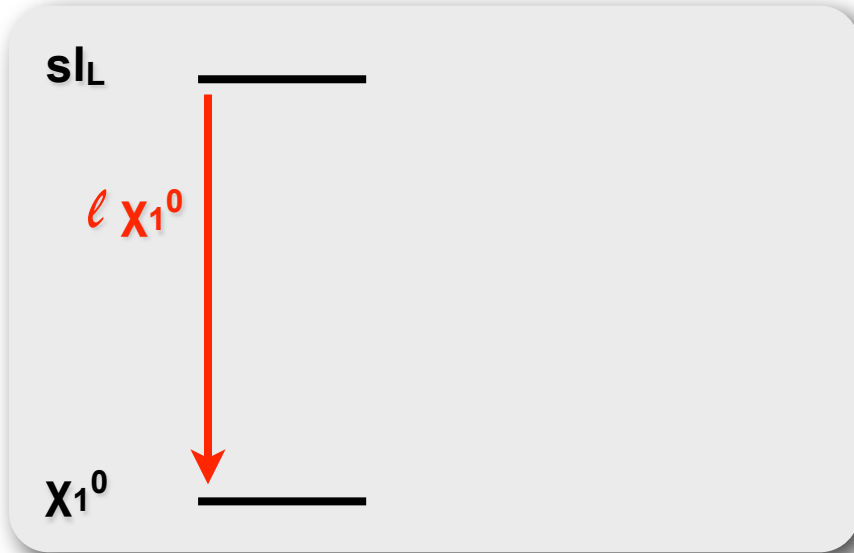
dilepton + MET

ATLAS, 1403.5294

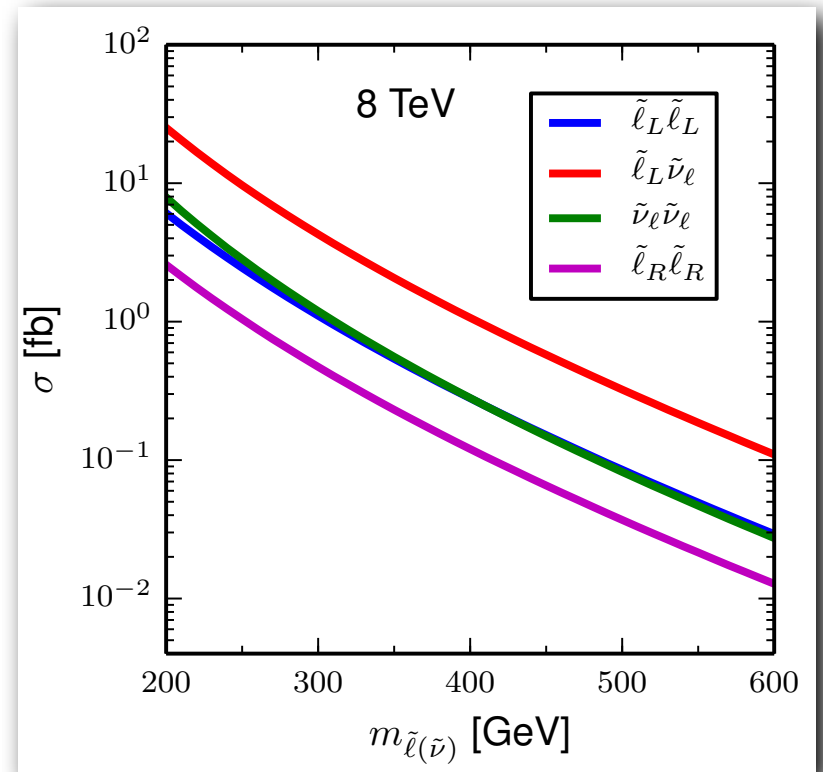


- 100% Br?
- sl sl production?

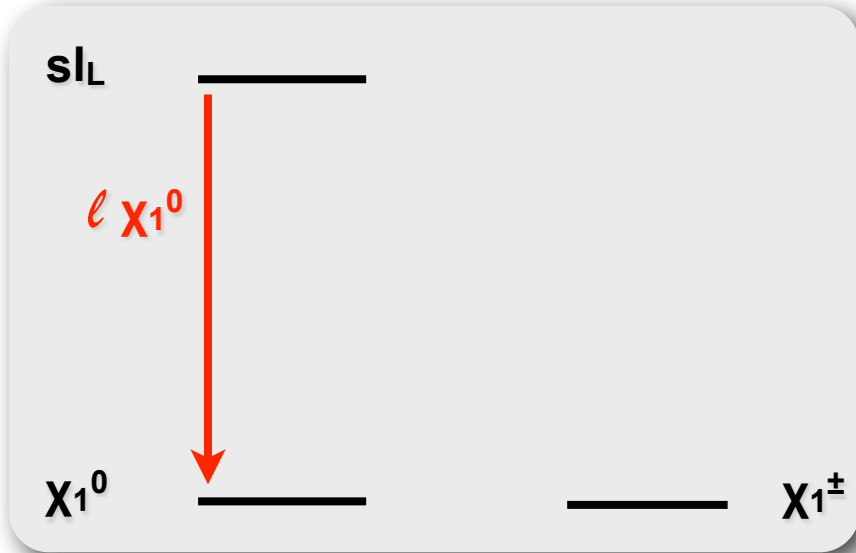
Decay of slepton



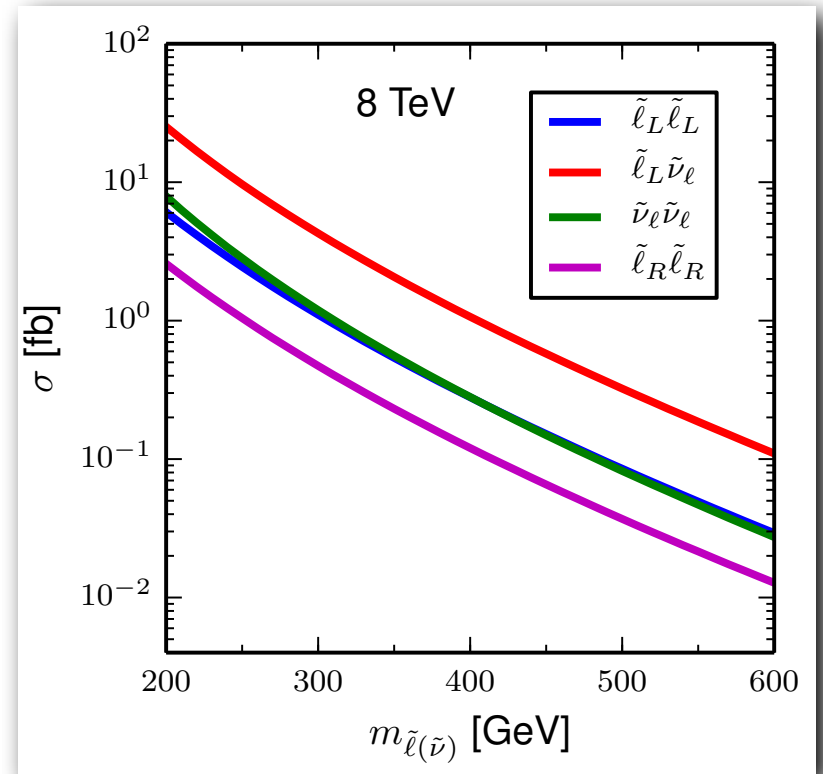
Wino-like LSP



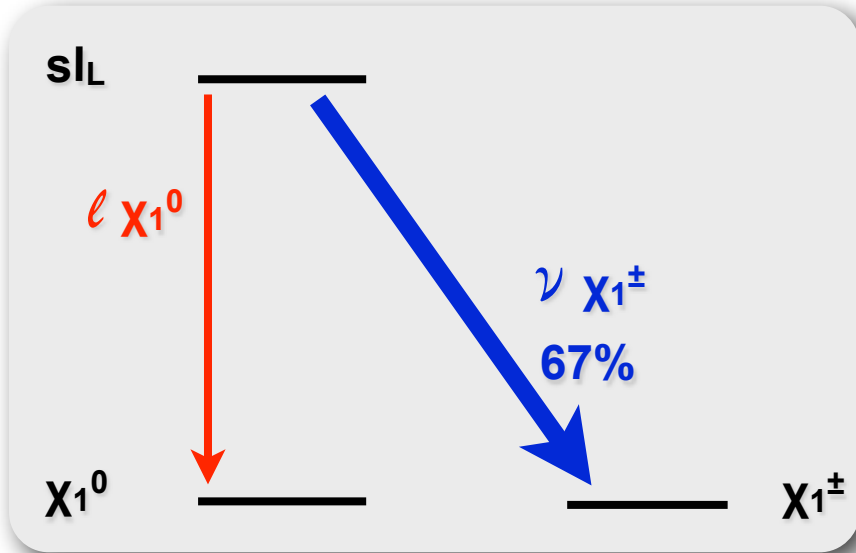
Decay of slepton



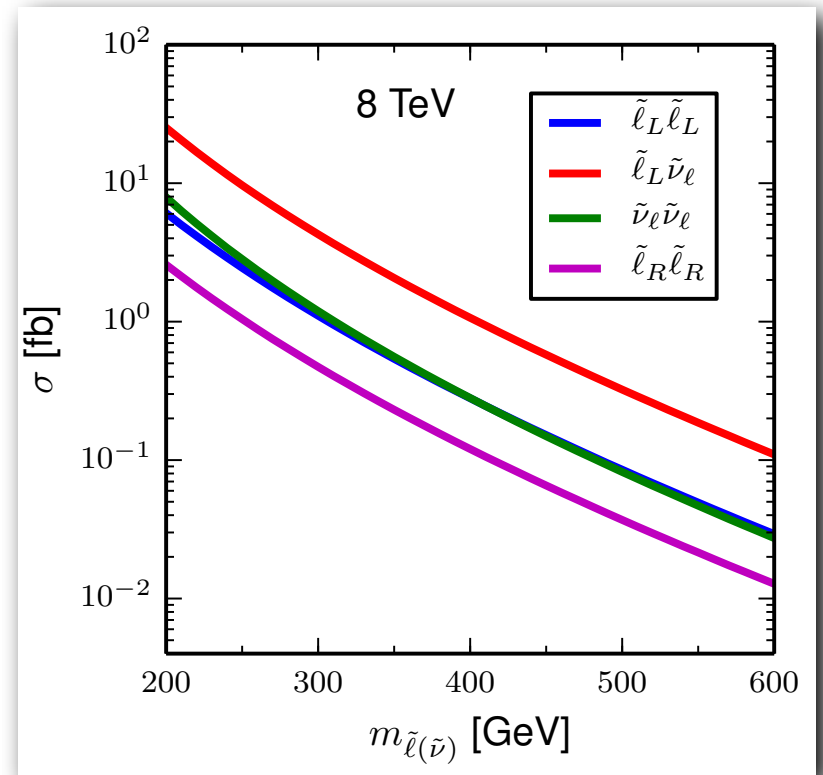
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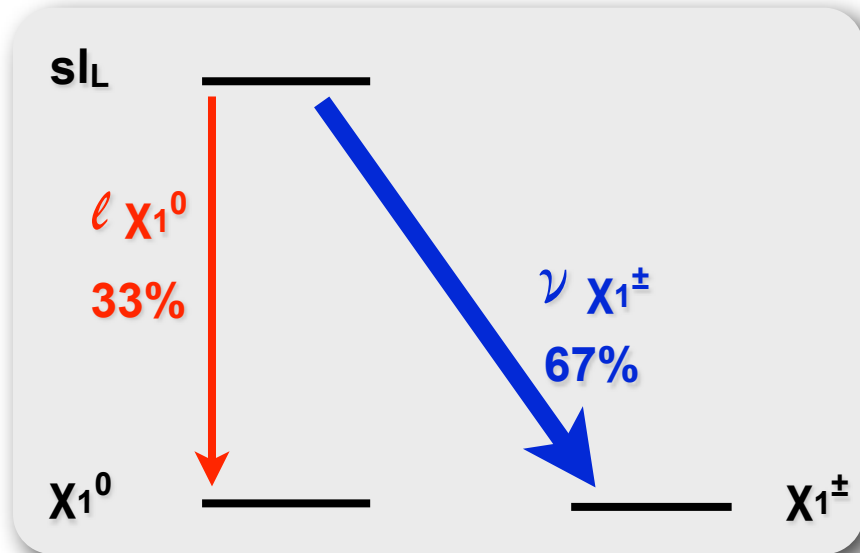
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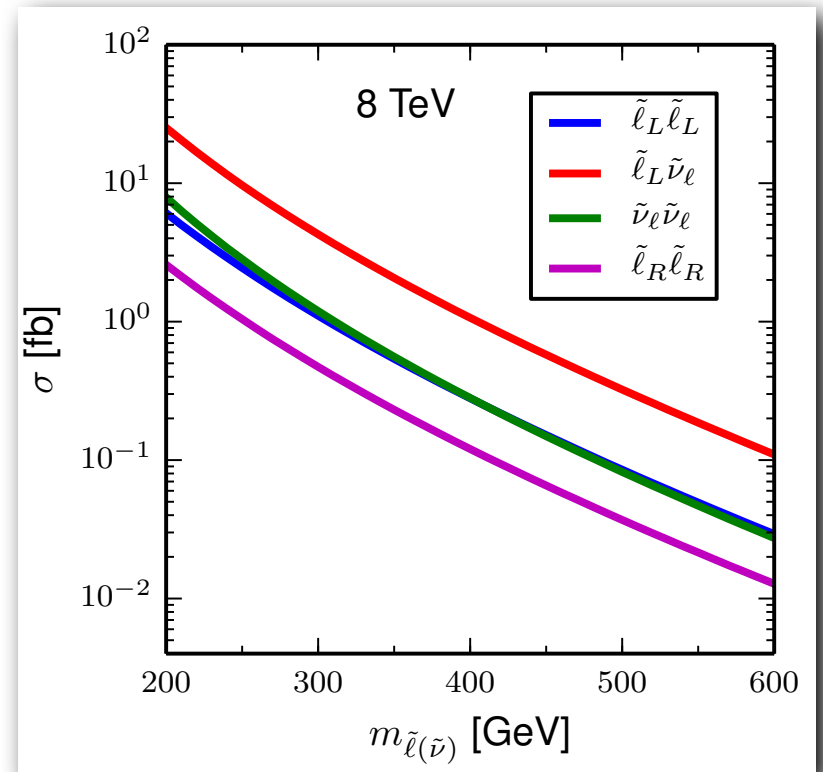
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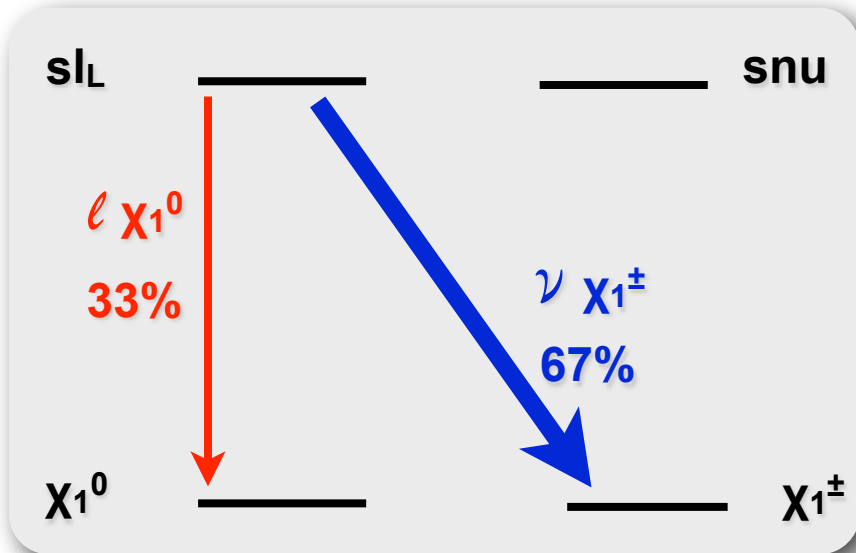
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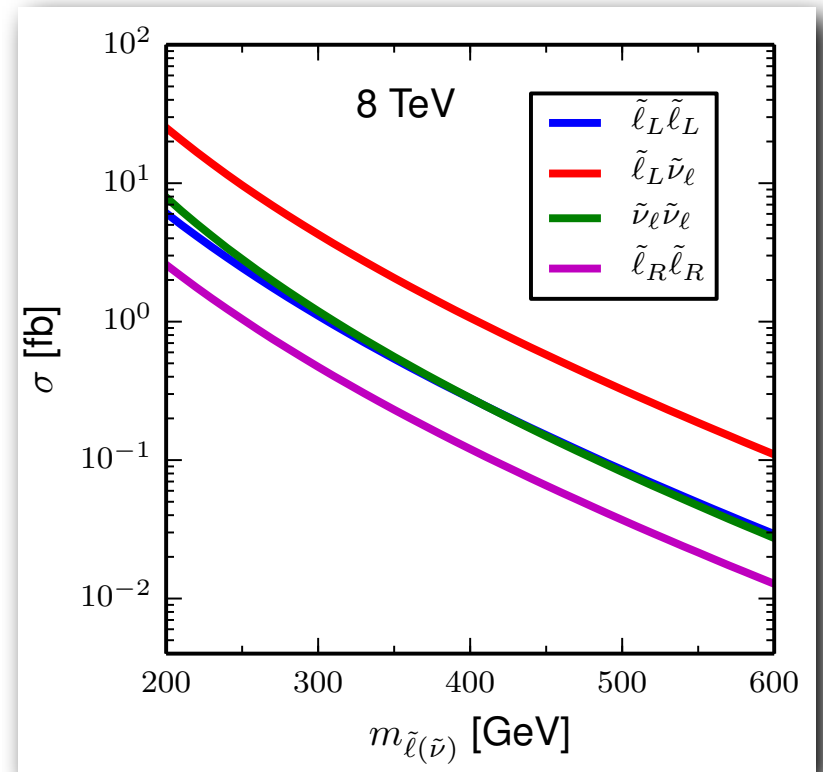
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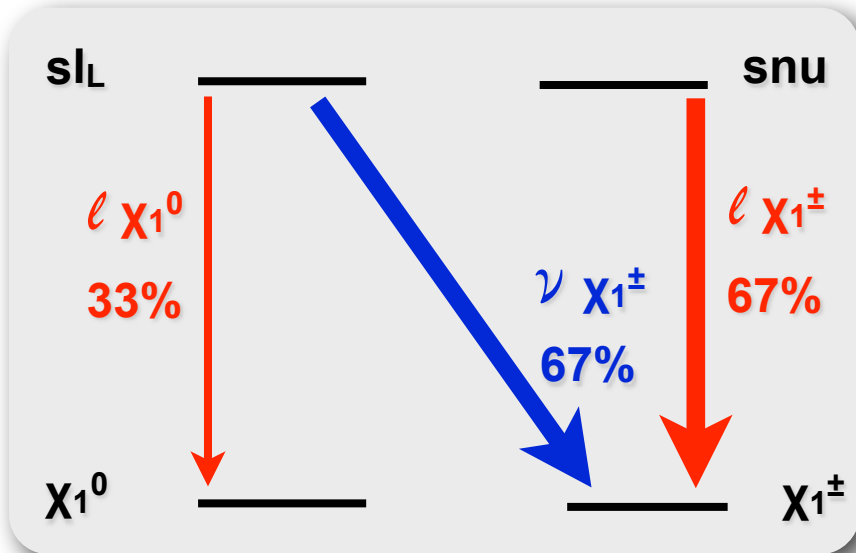
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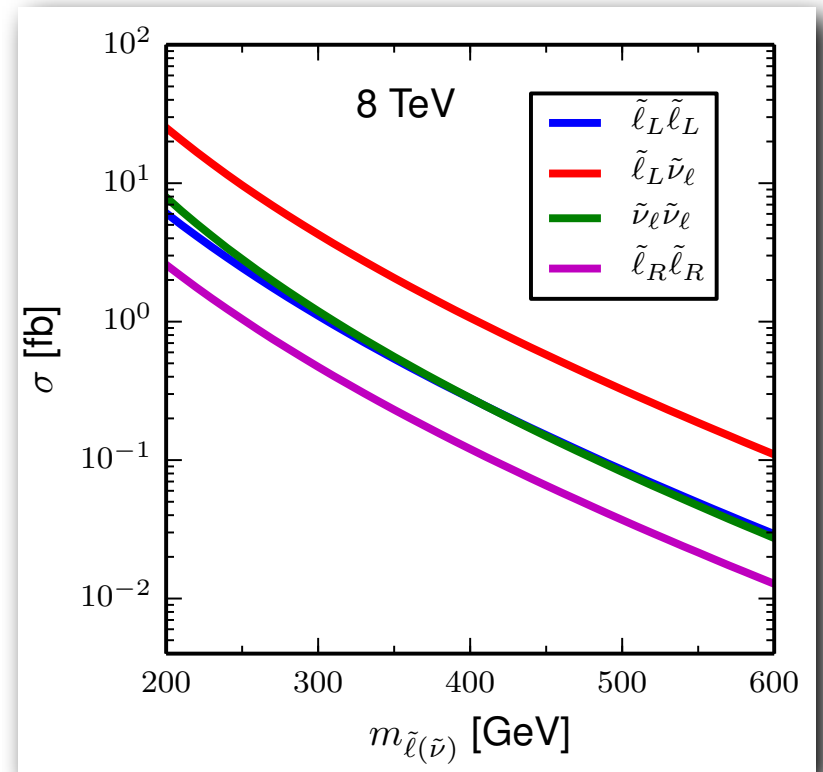
Wino-like LSP



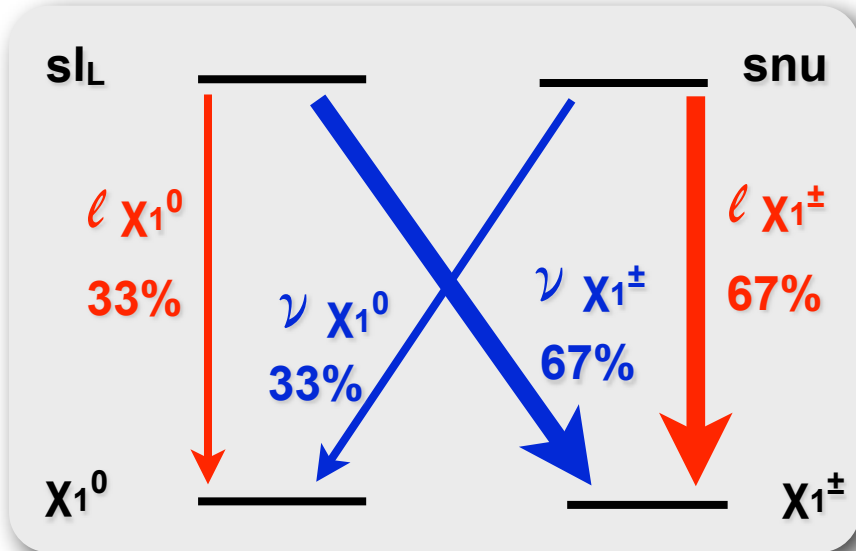
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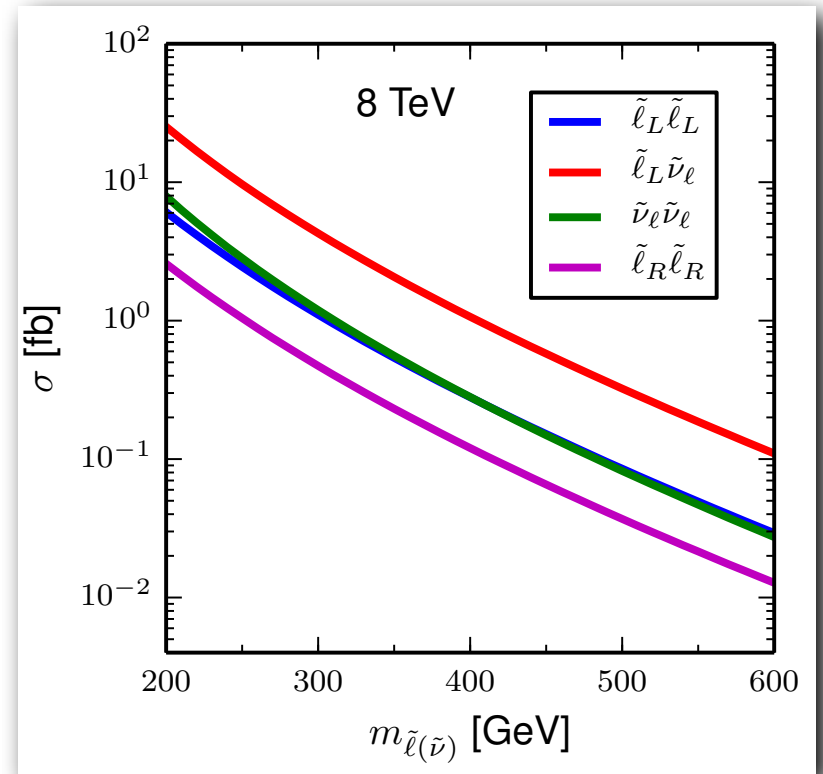
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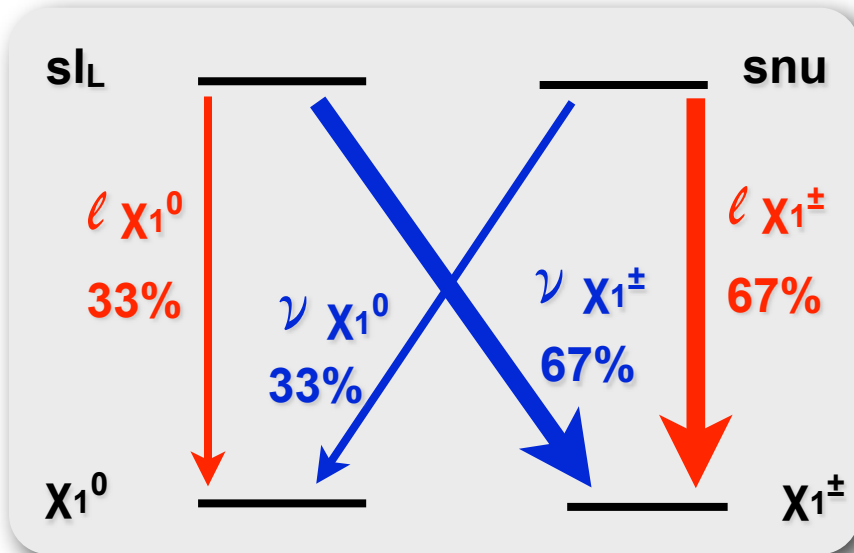
Decay of slepton



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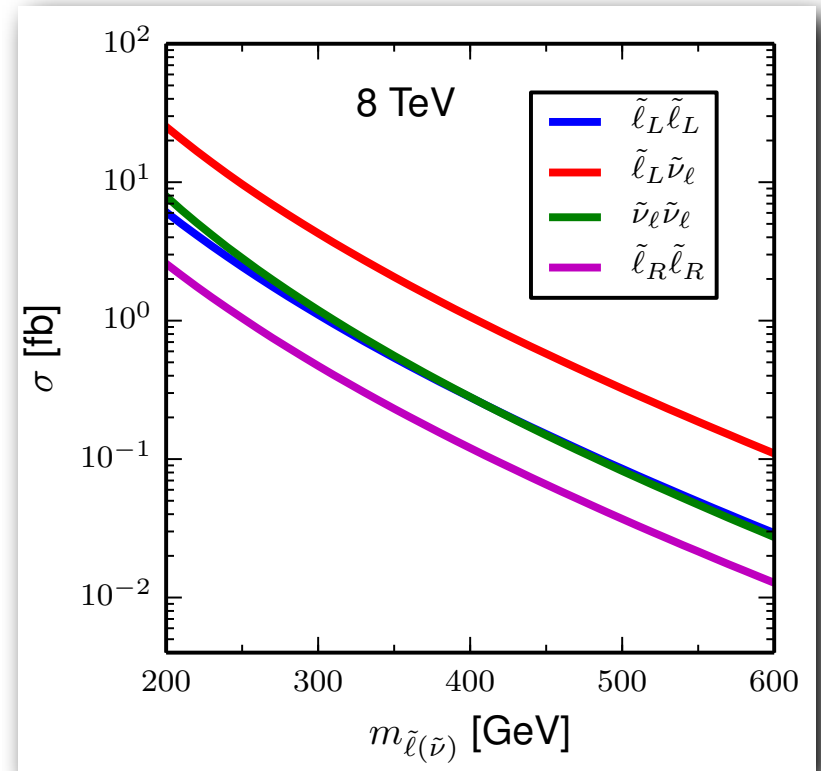


Decay of slepton

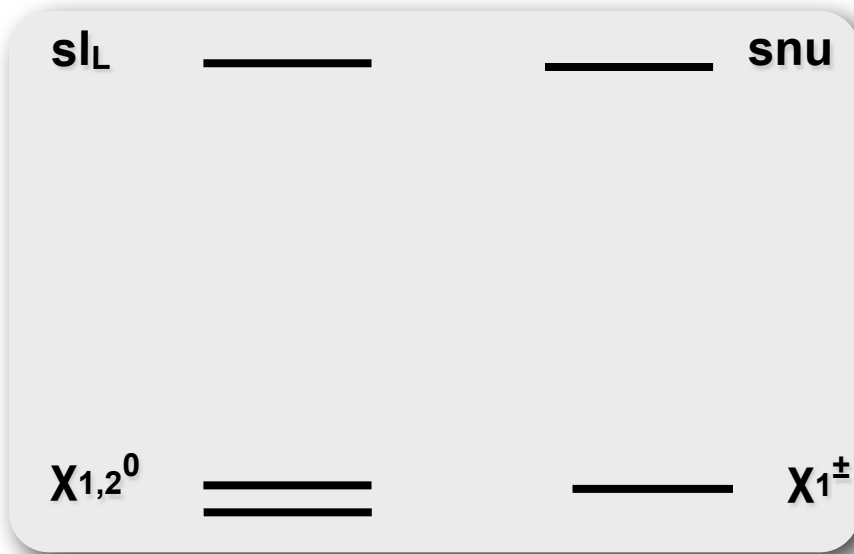


Wino-like LSP

- $sl_L \rightarrow \ell X_1^0$ Br suppressed
- $snu \rightarrow \ell X_1^\pm$ contribute
- $sl_L sl_L, sl_L snu, snu snu$ all contribute

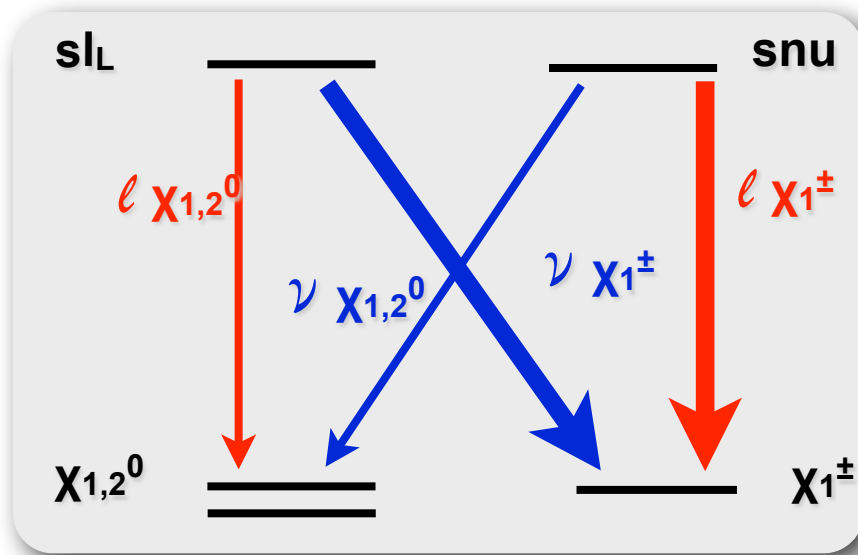


Higgsino LSP case



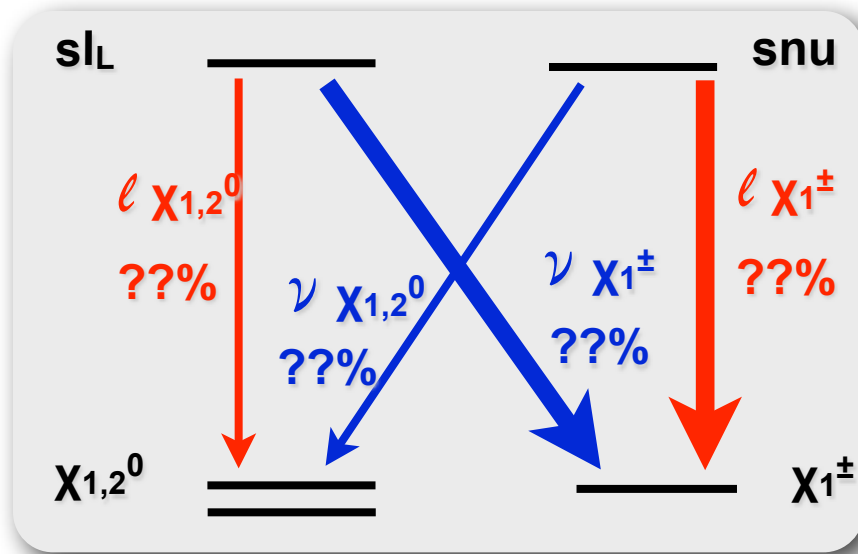
Higgsino-like LSP

Higgsino LSP case



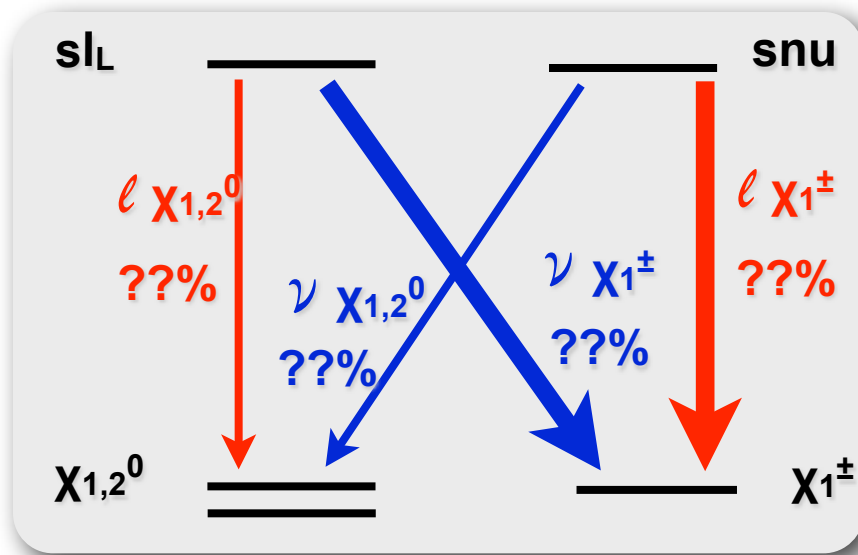
Higgsino-like LSP

Higgsino LSP case



Higgsino-like LSP

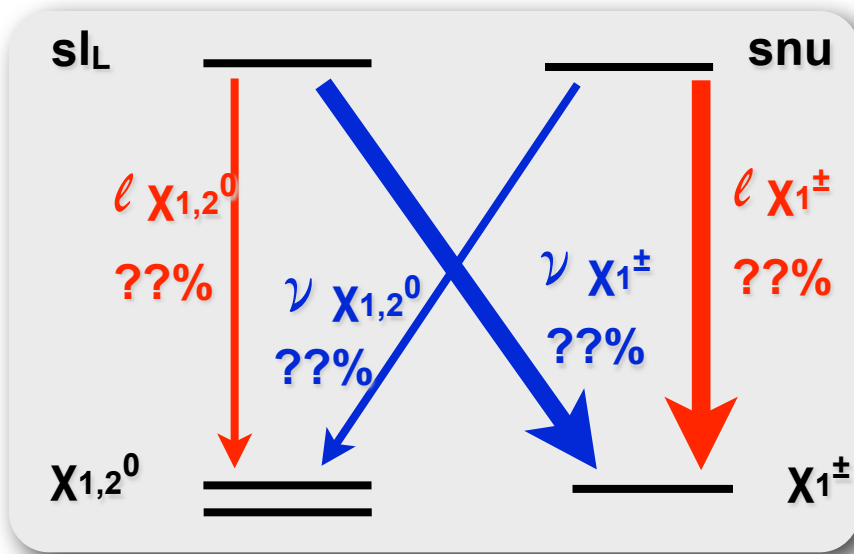
Higgsino LSP case



Higgsino-like LSP

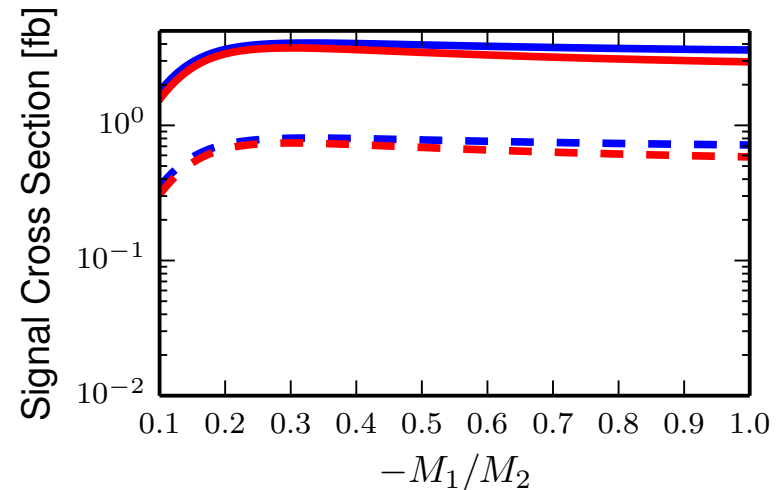
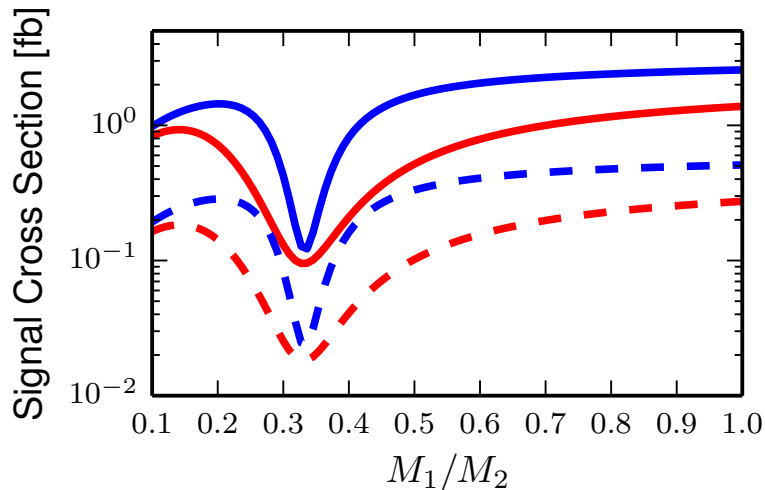
- depend on M_1/M_2
- sign of M_1/M_2 matters

Higgsino LSP case

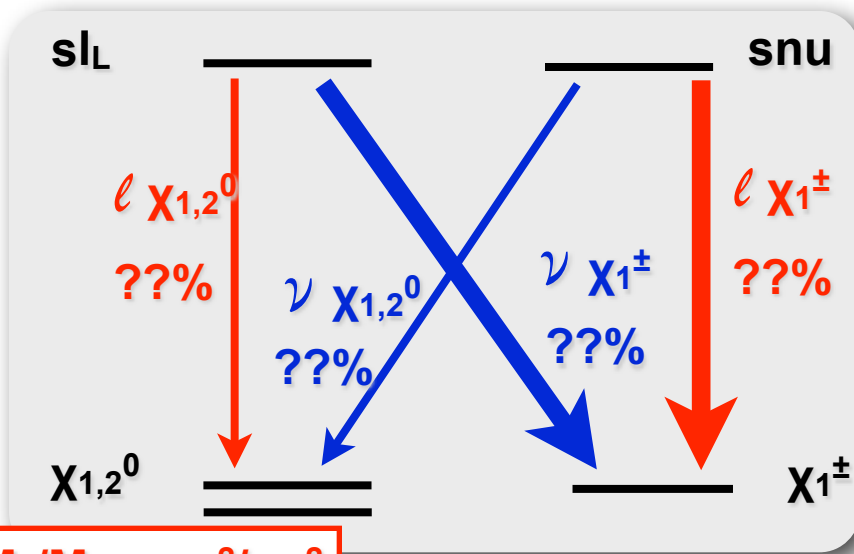


Higgsino-like LSP

- depend on M_1/M_2
- sign of M_1/M_2 matters



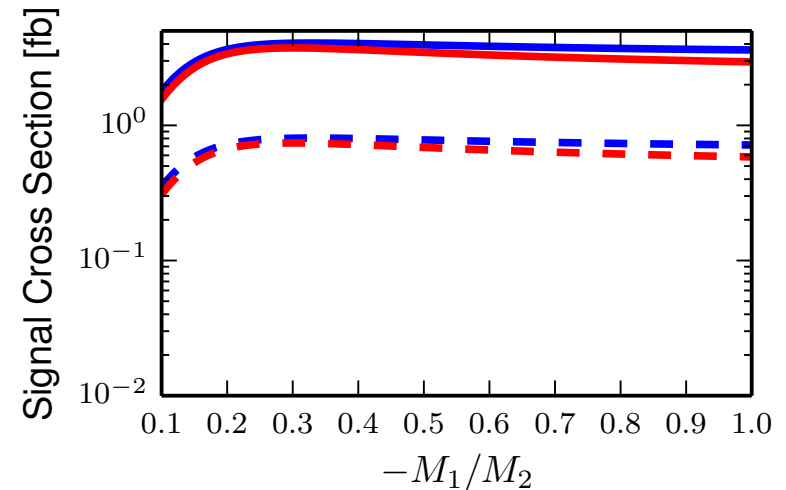
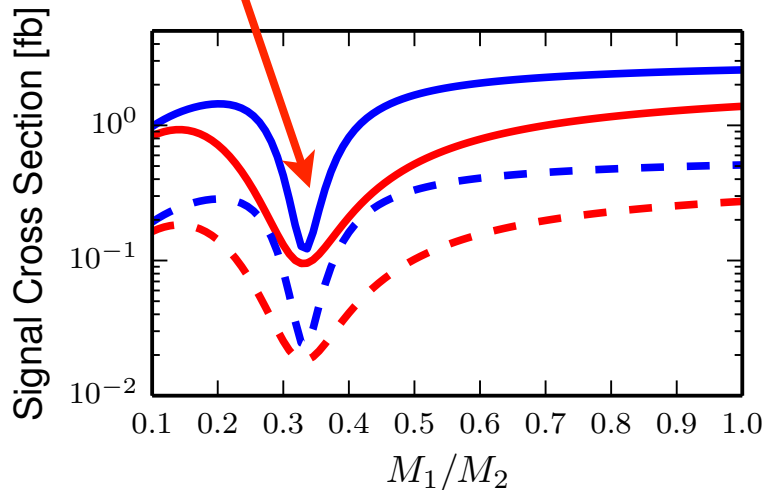
Higgsino LSP case



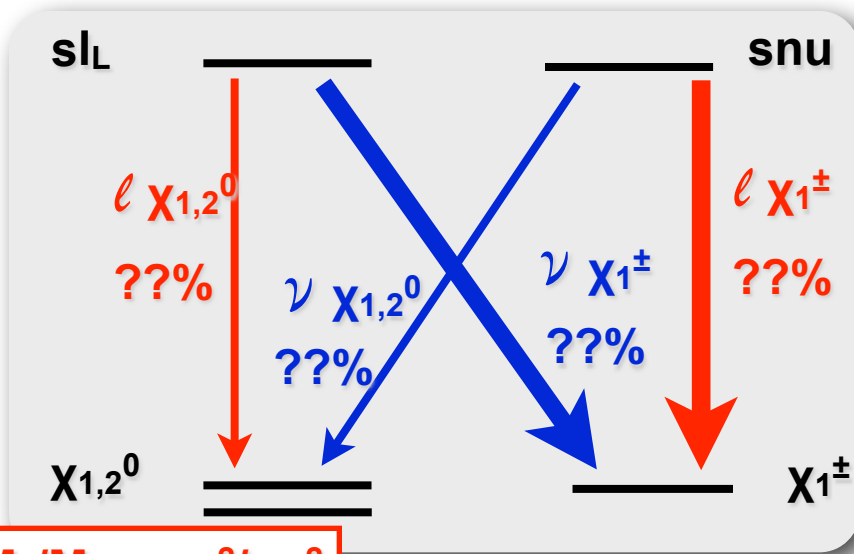
Higgsino-like LSP

- depend on M_1/M_2
- sign of M_1/M_2 matters

$$M_1/M_2 = s_W^2/c_W^2$$



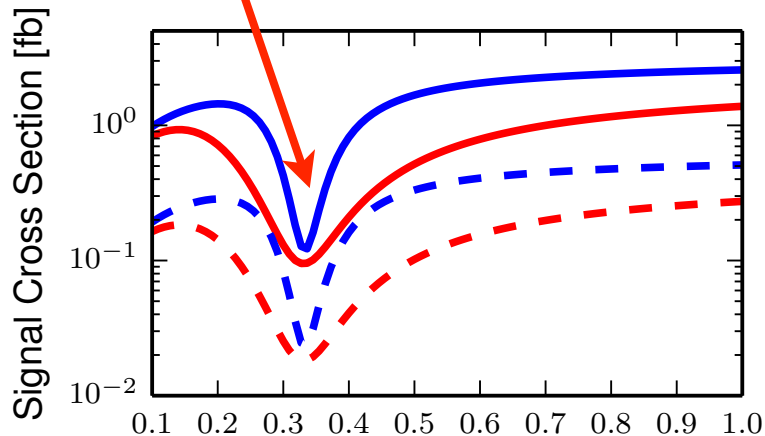
Higgsino LSP case



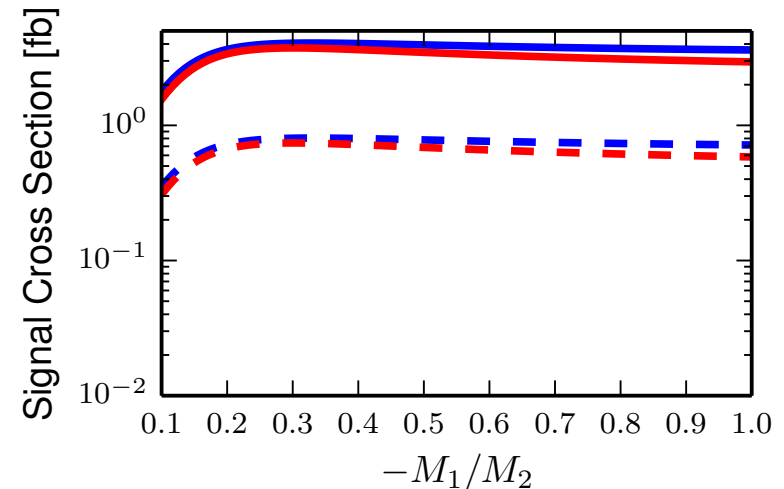
Higgsino-like LSP

- depend on M_1/M_2
- sign of M_1/M_2 matters

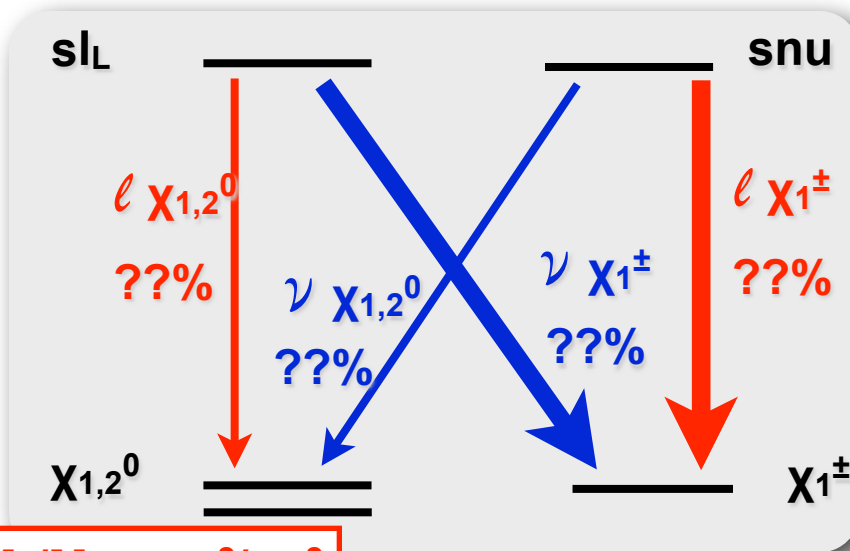
$$M_1/M_2 = s_W^2/c_W^2$$



Worst case!



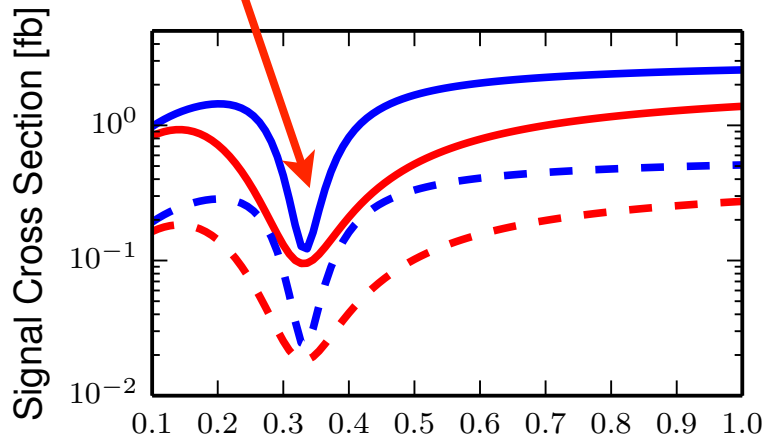
Higgsino LSP case



Higgsino-like LSP

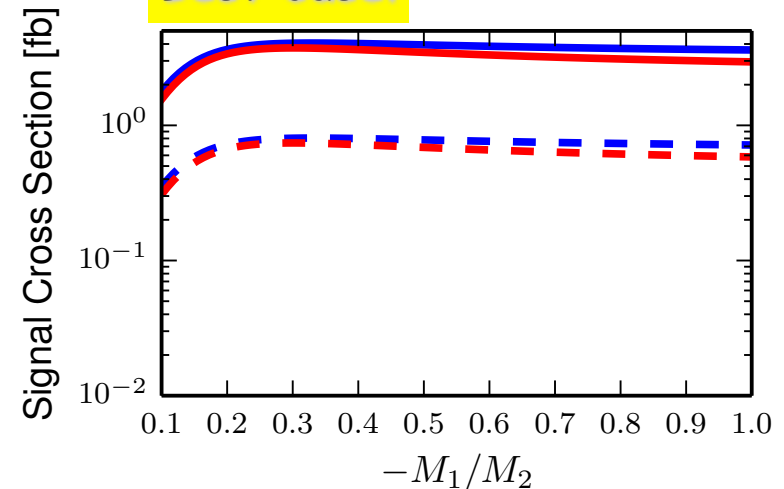
- depend on M_1/M_2
- sign of M_1/M_2 matters

$$M_1/M_2 = s_W^2/c_W^2$$

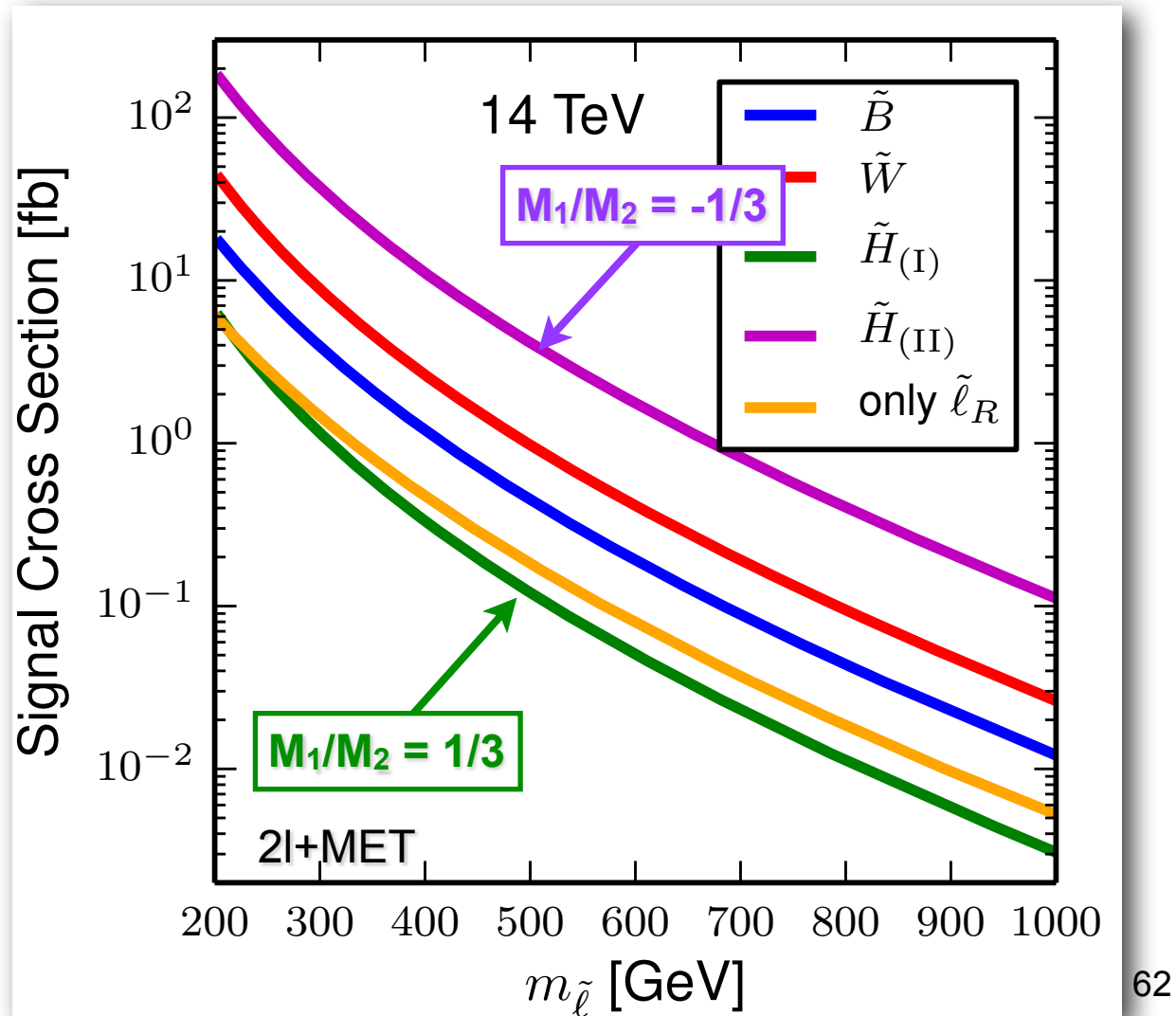


Worst case!

Best case!



2L+MET cross sections



LHC: Sleptons

Eckel, Ramsey-Musolf, Shepherd, Su (2014)

